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15th and 16th May 2025

Organized By

Dr. Sudhir Chandra Sur Institute of Technology and Sports Complex,
a NAAC 'A' accredited autonomous institution affiliated with MAKAUT
Surer Math, Kolkata, India

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Multimode Digital Modulator Design

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ABSTRACT

This paper presents the design and implementation of a multimode digital modulator capable of performing Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), Phase Shift Keying (PSK), or Quadrature Phase Shift Keying (QPSK) modulation, based on the select input values. A major highlight of this work is its low power consumption and simplified circuitry, achieved without sacrificing throughput. Prototypes using the proposed architecture have been developed, and simulation results confirm their correct operation. Furthermore, synthesis and power analysis reports demonstrate that the prototypes achieve high throughput with very low power consumption.

Keywords: Digital Multimode Modulator, Tanner tools, ASK, FSK, PSK, QPSK.

I. INTRODUCTION

In recent years, there has been significant research interest in universal digital modulators capable of supporting multiple modulation schemes [1]. These modulators are especially valuable in scenarios where real-time switching between modulation techniques is required. For example, in adaptive wireless communication systems, baseband processing algorithms may need to adapt to variations in environmental conditions, shifts in communication standards, or to improve overall quality of service. The development of multimode modulators (also referred to as universal modulators by some researchers) has generally followed two main approaches. One approach involves identifying the fundamental building blocks needed for various target modulation schemes and then combining these blocks to create a multimode modulator, either with or without hardware optimization. An example of such an architecture designed for software-defined radio is presented in [2]. Although the architecture was reconfigurable and implemented using a Field Programmable Gate Array (FPGA), it remained unsuitable for communication applications with strict power and area constraints due to its high resource demands.

The second approach to universal modulator design, which involves implementations based on the CORDIC algorithm and/or Direct Digital Frequency Synthesis (DDFS), has been explored in [3]–[8]. However, CORDIC-based architectures tend to be complex and offer limited computational speed, while DDFS-based designs face challenges related to restrict operating ranges and reduced spectral purity. In light of these limitations, the present work concentrates on designing and implementing a multimode digital modulator that minimizes silicon area and power consumption, making it well-suited for digital communication systems with strict area and power constraints, all without sacrificing operational speed.

In this paper the architecture of the proposed modulator has been detailed in section 2. The architecture has been validated using the Tanner EDA Tool in section 3. Results from the synthesis along with their analysis and comparison with other reported works have been included in section 4 and section 5 of the paper deals with concluding notes and future scope of the work.

II. PROPOSED MODULATOR ARCHITECTURE

The basic block diagram of the proposed modulator has been presented in fig.1. It is a multimode modulator in the sense that it can operate in any one of the ASK, FSK, PSK and QPSK modulation mode depending on the value of the control signals S0 and S1. The modulator is made up of simple digital subcomponents like 2:1 multiplexers, binary inverters, AND gates, NAND gates, D flip flops and appropriate carrier and clock signals. Apart from the select and data inputs, the modulator requires two carrier signals (C1 and C2) and two clock signals (CLK0 and CLK1) as inputs. The total architecture is divided into two blocks. The upper block performs ASK, FSK and PSK modulation schemes whereas the lower block is for QPSK modulation. The principle of operation of the proposed modulator in various modulation modes and the corresponding values control signals has been discussed below.

1. Operation of the proposed modulator in a ASK

The architecture works in ASK mode when the select inputs are set to 0 and 0 for S0 and S1 respectively.

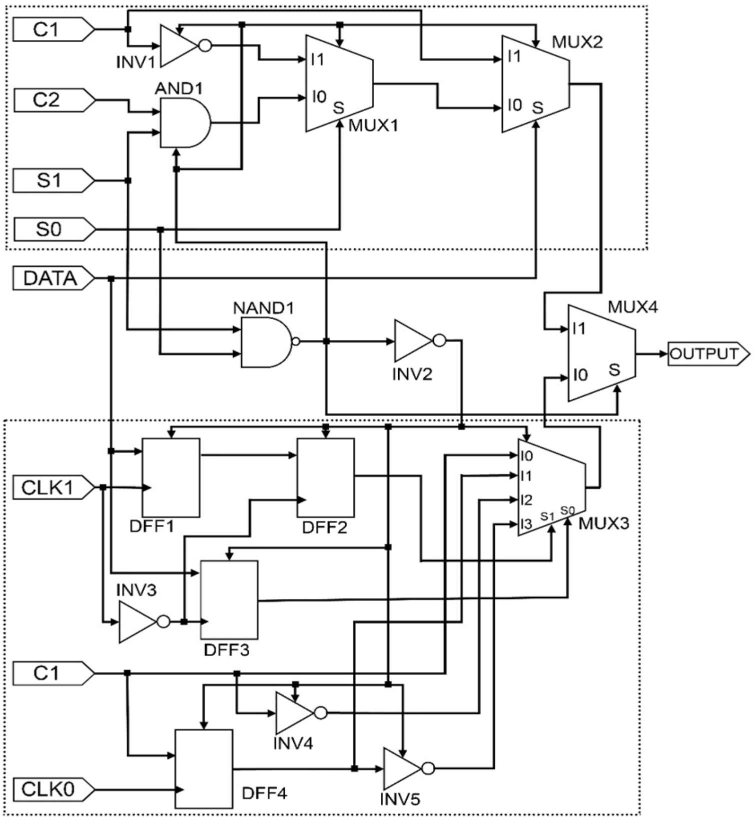


Fig.1 Block diagram of the proposed modulator

When S1 is 0, the output of AND1 is 0, which is connected to I0 of MUX1. As S0 is 0, regardless of the value of the input I1, the output of MUX1 will always be 0 which is connected to the input I0 of MUX2. The input I1 of MUX2 is connected with the carrier signal C1 and the data input is connected to the select line. Depending on the value of binary data, either 0 or C1 will be propagated to the output of MUX2 and fed to the input I1 of MUX4. The select line of MUX4 is driven by the output of NAND1, which will be 1 when S1 and S0 are both 0. Thus, the final output will be the ASK modulated signal.

2. Operation of the proposed modulator in a FSK

When the control signals are set to 0 and 1 for S0 and S1 respectively, the carrier signal C2 is prorogated to the input I0 of MUX1 through AND1. The carrier signal C1 is connected to the input I1 of MUX2. Depending upon the binary data input, either carrier signal C1 or C2 will be selected as the output of MUX2 and will be propagated to the input I2 of MUX4. This value itself will be the final output of the circuit as the select input of MUX4, driven by NAND1, is 1.

3. Operation of the proposed modulator in a PSK

When the value of the control signal S0 is 1, the output of MUX1, which in turn is connected to I0 of MUX2, is the carrier signal C1 with 180 phase shift. The carrier C1, with its original phase, is connected with I1 of MUX2. The output from NAND1, which is connected to the select line of MUX4, is 1. The input data selects either the carrier C1 or inverted C1 at MUX2, which is propagated as the final output, through the input I1 of MUX4.

4. Operation of the proposed modulator in a QPSK

When the values of both control signals S0 and S1 are 1, the output of NAND1 is 0. In this case, the final output from MUX4 is driven by the input I0, which is the output of MUX3, from the lower block. QPSK modulation scheme requires four phase shifted carrier frequencies. In order to obtain these, the carrier C1 is passed through INV4, producing a 180 phase shifted version of C1. The original C1 is also connected to a D flip flop (DFF4) to obtain the 90 phase shifted carrier, which is again passed through INV5 to get the 270 phase shifted carrier. The four carriers thus obtained are connected to inputs I0, I2, I1 and I3 of MUX3 respectively. It must be noted that for the 90 and 270 phase shifting circuit to work as intended, the frequency of CLK0 must be exactly double the frequency of the carrier C1. The input binary data is passed through a serial to parallel converter to separate out the di-bits. The serial to parallel converter consists of DFF1, driven by CLK1, and DFF2 and DFF3, driven by the inverse of CLK1. The clock CLK1 must be synchronous to the input data. The separated di-bits are connected to the select inputs S0 and S1 of MUX3. Thus, depending on the value of the di-bits, one the four phase shifted carrier frequencies is selected as output of MUX3 which is also the final output obtained from MUX4.

5. Power saving feature of the proposed modulator

The proposed architecture has been made power efficient in two steps. First, as is commonly done, the number of components required and the interconnect circuitry has been kept minimal and simple. It can be deduced from the block diagram that the circuit requires five inverters, four one bit D flip flops, three 2×1 multiplexers, one 4×1 multiplexer, one two input logical AND, one two input logical NAND, which is a total of only 15 basic components.

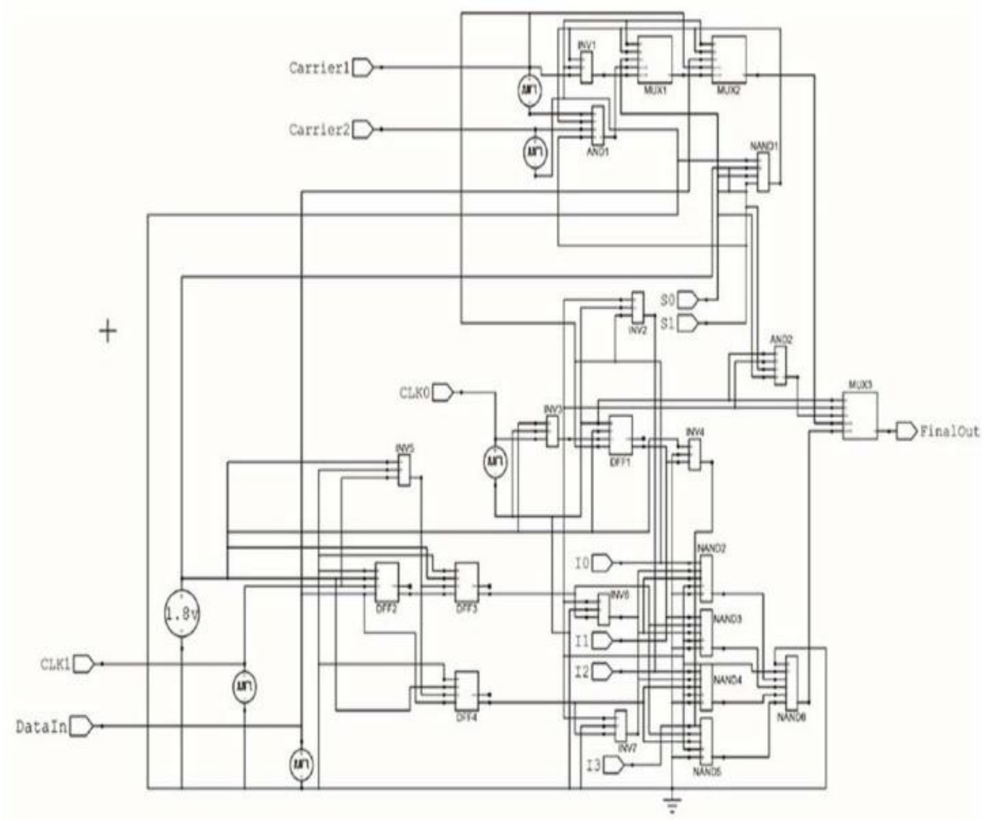
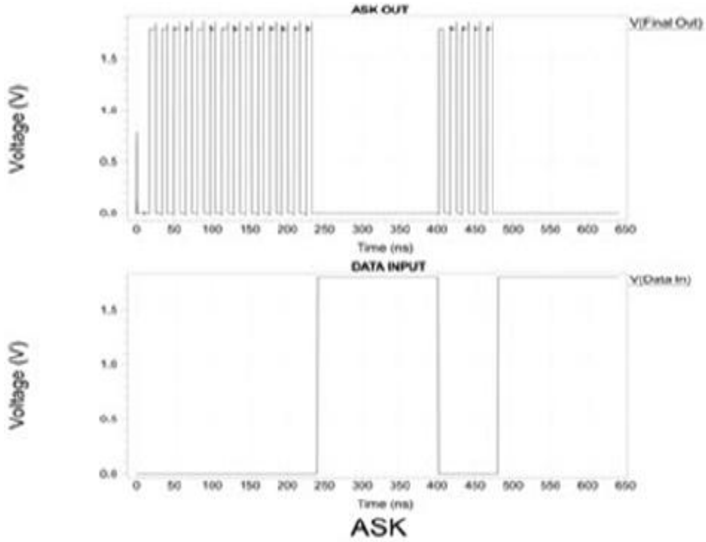


Fig.2 Schematic diagram of the proposed modulator using Tanner EDA tool

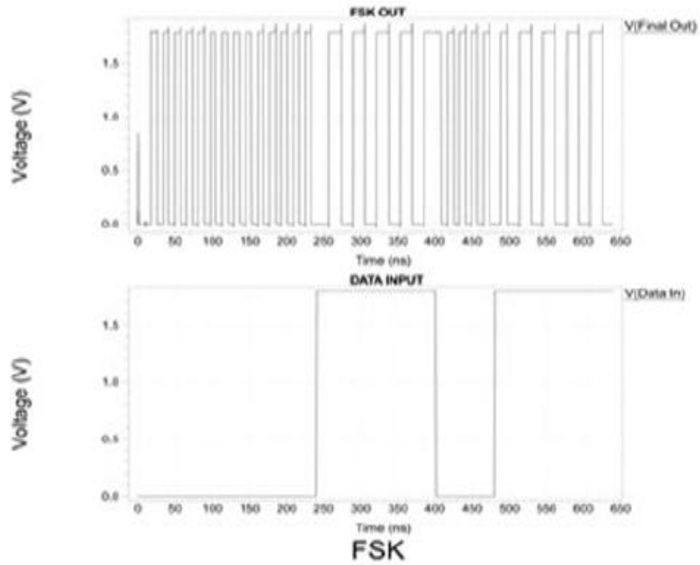
The interconnections amongst these components is also simple with minimal fan-out. Thus, power requirement and dissipation will be very low. Second, the architecture has been such designed that during operation only the components necessary for the selected modulation scheme are supplied power and switched on. Specifically, when the logical NAND (NAND1) of the selects inputs S0 and S1 is high (as for ASK, PSK and FSK), the upper block is turned on while the lower block remains turned off and consumes negligible power. The reverse happens when the output of NAND1 is low (for QPSK) and the corresponding output of INV2 is high, which supplies voltage to the lower block. This turns on the lower block and the upper block remains unpowered.

III. EXPERIMENTAL RESULTS AND ANALYSIS

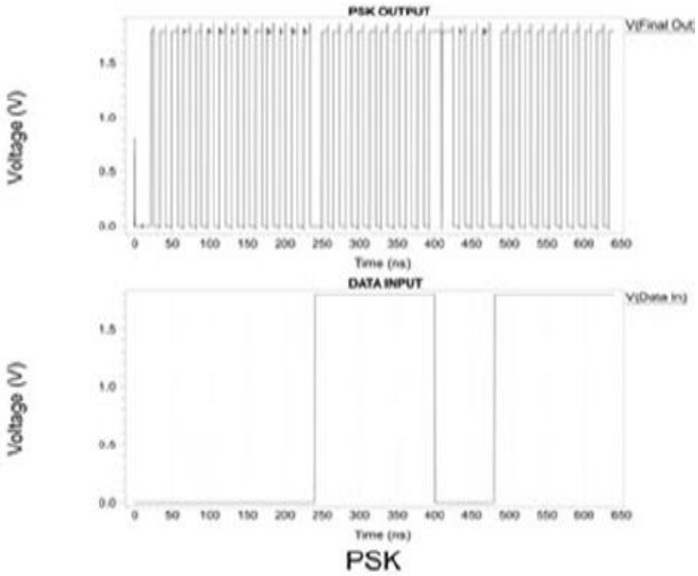
The prototype for the proposed architecture was designed using Tanner EDA Tool. The bottom up approach was used to develop the prototype. The basic gates were first implemented at the CMOS level and the other components were created using these basic gates. The design at the CMOS level ensured that all gates consist of minimal number of CMOS units. It was also ensured that the NAND and INV gates are capable of driving power to other components through their outputs. The final circuit of the prototype is shown in fig.2. The functionality of the prototype was tested by simulation and a portion of the obtained waveforms is provided in fig.3. The prototype was tested with 1.8V and 2.5V supply voltages and was found to be valid.


ASK OUT
V(Final Out)
Voltage (V)
Time (ns)
DATA INPUT
V(Data In)
Voltage (V)
Time (ns)
ASK

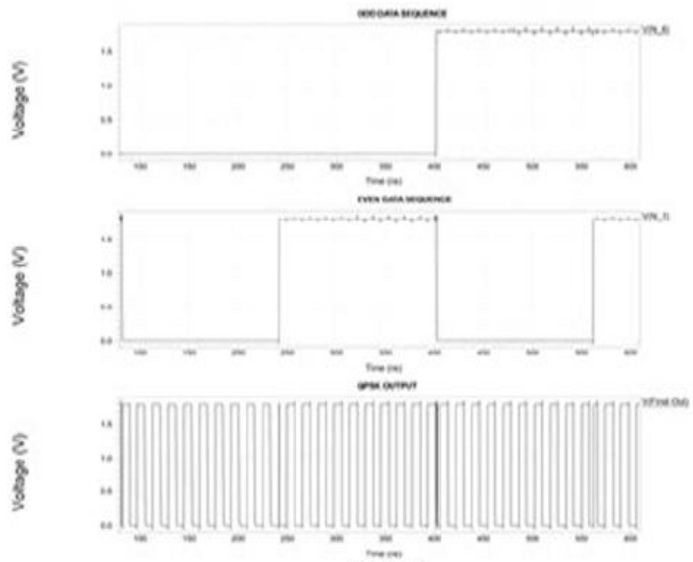
a)


FSK OUT
V(Final Out)
Voltage (V)
Time (ns)
DATA INPUT
V(Data In)
Voltage (V)
Time (ns)
FSK

b)


PSK OUTPUT
V(Final Out)
Voltage (V)
Time (ns)
DATA INPUT
V(Data In)
Voltage (V)
Time (ns)
PSK

c)



QPSK

d)

Fig.3 Simulated waveforms from the Tanner EDA tool implementation: a) ASK, b) FSK, c) PSK, d) QPSK

The prototypes, one targeting with CMOS units were tested for their performance and power consumption and dissipation. The results obtained have been summarized in Table 1. The prototypes were found to have a considerably larger power requirement. The explanation is twofold. The proposed architecture features a simple, but dynamic, power management circuitry which controls whether power is to be supplied to a component or not. However, since it is not possible to control the power supply to individual slices. The prototype designed at the CMOS level is capable of performing dynamic power management, hence consumes very less power. The added advantage of dedicated circuitry is low propagation and time to output delays. The performance and power requirements of the proposed architecture was compared with the results reported in related literature [2]-[8]. Although a direct comparison could not be made, largely due to difference in the set of modulation schemes implemented in the existing work, it could be generally observed that the performance proposed architecture is at par or superior to them. Also, the power consumption reported in the existing work was found to be higher in all cases considered.

IV. CONCLUSION

A multi-mode digital modulator was proposed and prototyped in this paper, with the target of achieving high throughput and very low power requirement. Two prototypes, one based on using CMOS units, were developed. The CMOS based implementation met all expectations, including very low power requirement. This work can be further taken in two directions. One, other sets of related and relevant modulation schemes may be used with the same key targets. The scope of this work encompasses all digital communication requiring high speed and low power multimode modulators.

Table – 1 Performance Comparison

Parameter	**MOS 1.8V**	**MOS 2.5V**
Power (mW)	0.95 – 2.66	2.15 – 6.69
Propagation Delay (ns)	0.63	0.63
Delay Time (ns)	0.52	0.52

Parameter	MOS 1.8V	MOS 2.5V
MOSFETS	238	238
Max. Stable Operating		
Freq. (MHz)	62.5	62.5
Max. Carrier Freq. (MHz)	500	500
Data Rate (Mbps)	125	125

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Real-Estate Price Prediction Using Machine Learning

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ABSTRACT

Real estate pricing is influenced by various factors such as location, amenities, property size, and economic conditions. This study focuses on predicting real estate prices in Bangalore using machine learning models. We explore multiple regression-based techniques, including linear regression, decision trees, and artificial neural networks, to develop an accurate pricing model. The dataset used consists of historical property transactions in Bangalore. The study aims to assist homebuyers, sellers, and real estate investors in making data-driven decisions..
Keywords: Real estate, Machine Learning, Price Prediction, Bangalore, Regression Models

I. INTRODUCTION

Real estate prices are a multifaceted issue depending on several variables like locality, infrastructure, road connectivity, and market forces. Classical models are unable to estimate nonlinear interactions between variables. Machine learning (ML) algorithms provide a computationally effective way to forecast real estate prices by finding patterns in historical data. We investigate various ML models to predict real estate prices in Bangalore in this paper and compare their performances using different measures

II. LIFE CYCLE OF MACHINE LEARNING

Machine Learning Life Cycle is defined as a structured process that describes the phases of developing and sustaining a machine learning model from start to finish. It begins with Problem Definition, under which the problem to be addressed via machine learning is clearly defined. The business requirement is evaluated, the desired outcome is established, and the proper type of machine learning task—like classification, regression, or clustering—is established. By defining the problem properly, the entire ML project's direction is established.

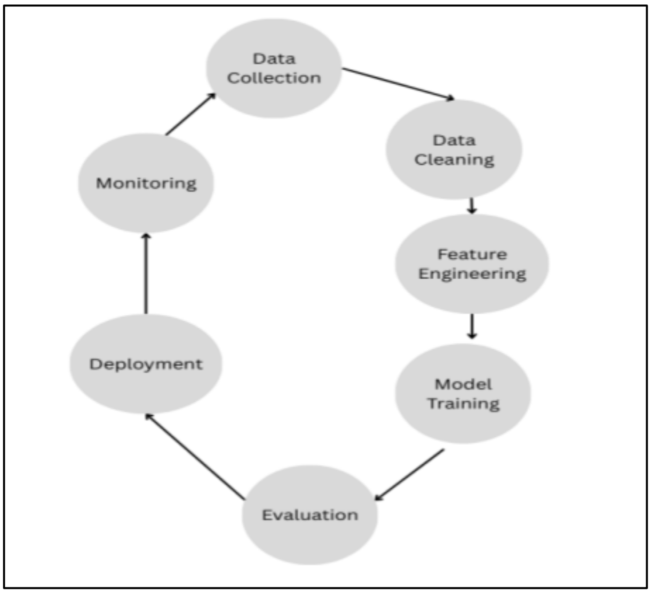

Fig1: Machine Learning LifeCycle

Subsequent to this, the process is resumed with Data Preparation, which is regarded as one of the most important and time-consuming phases. During this phase, data is gathered from various sources, cleaned, and structured. Missing values are treated, outliers are eliminated, and the data is converted into a proper format for modelling. It is generally accepted that the quality of the data significantly affects the performance of the final model.

After the data has been prepared, Model Development is the subsequent step. The right algorithms are chosen depending on the problem and the type of data. The dataset is split into training and testing sets, and the model is trained on the training set. Its performance is then measured using metrics like accuracy, precision, recall, or mean squared error. At this point, hyperparameters can be optimized and validation methods can be used to enhance the generalization of the model.

Once an acceptable level of performance has been reached, the model is transferred to the Model Deployment phase. Here, the trained model is incorporated into a production environment in which it can be utilized to make predictions or assist in decision-making. The model can be exposed via APIs, embedded inside software systems, or hosted on cloud platforms so that it can be accessed by users or other applications.

Lastly, the released model undergoes Monitoring. This phase guarantees that the model operates efficiently in the real world. The model's predictions and measures are constantly monitored, and any indication of performance decline is detected. In case data drift or environmental changes are noticed, the model can be retrained or recertified. With continuous monitoring, the reliability of the system is ensured, and feedback to previous stages of the life cycle is given to sustain improve me.

III. LITERATURE REVIEW

Existing studies in real estate price prediction leverage traditional statistical methods and modern machine learning models such as linear regression, decision trees, and ensemble techniques. Previous research highlights the significance of feature engineering and data preprocessing in improving prediction accuracy. However, most studies are generic and do not focus on Bangalore's unique real estate market.

This study builds on past work by implementing machine learning techniques tailored for Bangalore's property landscape, considering local economic and infrastructure developments.

Yu, H.et al. [1] developed models capable of accurately estimating house prices using both regression and classification techniques. The authors utilize a dataset from Ames, Iowa, comprising 79 features and 1,460 houses sold between 2006 and 2010. Regression methods such as Lasso, Ridge, Support Vector Machine (SVM) regression, and Random Forest regression are employed to predict exact prices. For price range classification, methods including Naive Bayes, logistic regression, SVM classification, and Random Forest classification are applied. Principal Component Analysis (PCA) is also performed to enhance prediction accuracy. In Ravikumar, AswinSivam's [2] dissertation explored the application of machine learning algorithms to predict real estate prices. The study focuses on identifying significant features influencing property prices and evaluating the performance of various machine learning models in forecasting these prices. The research aims to provide a reliable predictive model to assist stakeholders in the real estate market. In Dabreo, S., Rodrigues, S., Rodrigues, V., & Shah. Et al. [3] presented a study on predicting real estate prices using machine learning techniques. The authors collect and preprocess data, selecting relevant features that impact property prices. Various machine learning models are trained and evaluated to determine their effectiveness in predicting real estate prices. The study aims to provide insights into the applicability of machine learning in the real estate sector. In Mohd, T., Jamil, N. S., Johari, N., Abdullah, L., &Masrom.et al. [4] reviewed various modelling techniques applied in predicting house prices within the real estate industry. It discusses the challenges associated with housing price prediction and examines different regression models utilized in this domain. The study provides a comprehensive overview of the strengths and limitations of each modelling approach, offering valuable insights for researchers and practitioners in selecting appropriate methods for house price prediction. In Sarip, A. G., Hafez, M. B., &Daud,et al. [5] introduced a fuzzy least-squares regression-based (FLSR) model to predict real estate prices, addressing the non-linear relationship between property attributes and prices. The study conducts a comparative analysis of FLSR, Artificial Neural Networks (ANN), and Adaptive Neuro-Fuzzy Inference Systems (ANFIS). Findings reveal that FLSR offers superior prediction accuracy and lower computational complexity compared to ANN and ANFIS, making it a viable tool for real estate price prediction.

Yazdani .et al. [6] addressed biases in traditional real estate appraisals by developing data-efficient learning models to predict property prices. It compares the performance of machine learning algorithms—specifically artificial neural 9 networks (ANN), random forests, and k-nearest neighbors (KNN)—against traditional hedonic pricing models. The research, conducted using data from Boulder, Colorado, demonstrates that random forests and ANNs outperform hedonic regression analysis in accurately predicting house prices, highlighting the non-linear relationships between property features and their prices Mostofi, F., Toğan, V., &Başağa .et al. [7] focused on improving the accuracy of real estate price predictions for small-sized agencies by integrating Deep Neural Networks (DNN) with Principal Component Analysis (PCA). The study addresses challenges associated with high-dimensional datasets and limited data availability. Findings indicate that the combined DNN-PCA approach enhances prediction performance, making it a viable solution for agencies with constrained resourcesJa'afar, N. S., Mohamad, J., & Ismail .et al.[8] examined the application of machine learning techniques in property price prediction and valuation. It categorizes various algorithms, datasets, and evaluation metrics used in existing studies, providing a comprehensive overview of current methodologies. The review identifies trends, challenges, and future research directions, serving as a valuable resource for researchers and practitioners aiming to implement machine learning in real estate valuation.Uzut, O. G., &Buyrukoglu .et al. [9] explored the use of data mining algorithms to predict real estate prices. By analyzing a dataset containing various property attributes, the authors apply algorithms such as decision trees, support vector machines, and ensemble methods. The research demonstrates that data mining techniques can effectively model complex relationships in real estate data, providing accurate price predictions and valuable insights for stakeholders.Chiu, S. M., Chen, Y. C., & Lee .et al. [10] presented a real estate price prediction system that incorporates temporal and spatial features using a lightweight deep learning model. The proposed system captures the dynamic nature of real estate markets by considering time-series data and geographical information. The study demonstrates that the integration of these features into a deep learning framework enhances prediction accuracy, offering a practical tool for real estate valuation in rapidly changing markets.

IV. DATA COLLECTION AND PRE-PROCESSING

The data for this project is a dataset of real estate transactions collected from online house listings and government records. It contains detailed data of different dimensions of residential property that are important in analyzing and forecasting the price of real estate. Some of the key features in the data are the area type, i.e., super built-up area or plot area, and the status of availability of the property (ready to move or under construction). The data also records the location of the property, size in the form of number of bedrooms, halls, and kitchens (BHK), and the society or community name where the property is situated. It also provides the total floor area of the property, bathrooms, and balconies, as well as the sale price in terms of lakhs of rupees. All these features are vital variables that are used in building predictive models and identifying the intrinsic factors governing the price of property.

4.1. Data Cleaning

For ensuring that the dataset was clean and ready to be analyzed and modelled, various cleaning steps were taken on the data. Missing values were first tackled through imputation methods. Based on the type of data, either the mean or mode was employed to complete the missing values—numerical columns were generally imputed with the mean, whereas categorical attributes were completed using the mode. This ensured that the integrity of the dataset was preserved without losing useful entries.

Second, outlier identification and removal were conducted with both the Z-score technique and the Interquartile Range (IQR) method. Both of these techniques aided in the identification and removal of observations that were markedly different from most of the others, potentially skewing the model's accuracy and performance otherwise.

To prepare the data for machine learning models, categorical variables were converted to numerical form. This was done using one-hot encoding specifically for features like location and amenities available, so that algorithms can read and process these variables properly. Finally, all numerical features were normalized to put them onto the same scale. This ensured that no one feature unduly affected the model because of differences in scale, thereby enhancing both training stability and overall predictive performance.

4.2. Feature Engineering

Feature engineering was conducted to improve the quality and predictive power of the dataset. To begin with, the count of BHK (Bedroom-Hall-Kitchen) was derived from the size feature. This enabled the room count to be treated as a separate numerical feature, which could be utilized more effectively while training the model.

To correct discrepancies in the total square feet column, values expressed as a range (e.g., "1200 - 1500") were translated into numerical form by averaging them out. Standardization facilitated consistent processing and analysis of the area information. A new column, price per square foot, was also constructed by dividing the overall property price by the area in square feet. This metric derived was applied in order to enable better comparisons between properties of different sizes and locations.
Dimensionality was reduced by grouping rare or infrequently appearing locations under the umbrella label, "Other." This was a way of reducing noise and stopping the model from being biased by sparsely represented data points. The dataset was cleaned up and made more useful for training good and generalizable machine learning models through these actions.

V. METHODOLOGY

This study uses a variety of supervised machine learning algorithms to make predictions of house prices from a wide range of features related to the property. The models chosen reflect both basic and advanced regression approaches, ensuring that there is an even balance of predictive strength assessments. The dataset was cleaned beforehand to be in good quality and consistent form, involving steps such as dealing with missing values, encoding categorical variables, and performing feature scaling as required.
After pre-processing, the data was separated into training and test subsets for assessing the ability of the models to generalize. Several algorithms were run on identical data to find out their limitation and strength to identify patterns within housing data. Standard regression performance metrics were used to compare the output of models.

5.1 Linear Regression (LR)

Linear Regression is a basic statistical technique employed as a baseline model in this work. It presumes a linear interaction between the features (independent variables) and the target value (house price).

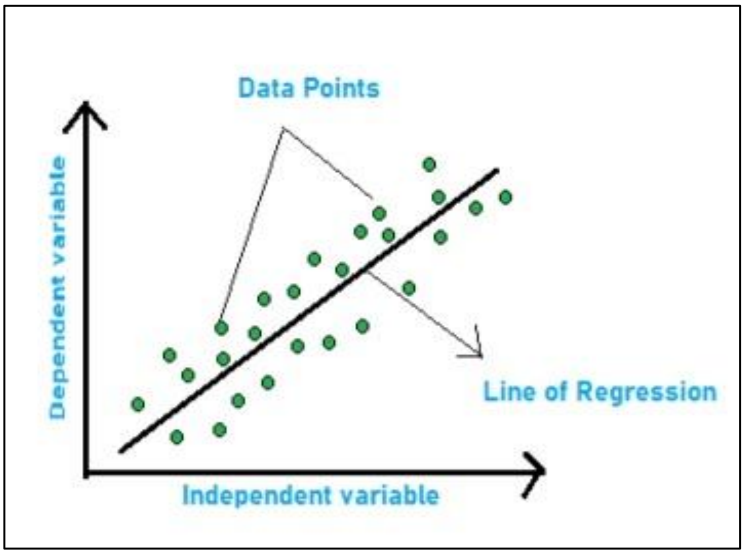

Fig 2: Linear Regression

Each feature is estimated with coefficients to be able to provide a best fit line minimizing discrepancy between predicted values and actuals via the method of least squares. Linear Regression is a simple and transparent base that makes for a great preliminary assessment of further complicated models.

5.2 Decision Tree Regressor (DTR)

The Decision Tree Regressor creates a model as a tree structure, where the data is divided into subsets on the basis of feature values. Each node is a decision rule, and each leaf is a predicted value. This model can learn non-linear relationships in the data without data normalization or transformation. It is, however, overfitting-sensitive, particularly when the tree becomes too deep. Methods like pruning or capping the maximum depth are usually used to counteract this problem.

5.3 Random Forest Regressor (RFR)

Random Forest is an ensemble learning method consisting of several decision trees. The trees are each trained on a random subset of the data and attributes, and their predictions averaged to give the final output. This ensemble methodology decreases variance and increases robustness, making the model more generalizable than individual decision tree. It is particularly useful in handling high-dimensional data and noisy datasets.

5.4 Gradient Boosting Regressor (GBR)

Gradient Boosting is an iterative ensemble technique wherein new models are learned to address the mistakes done by earlier models. In each iteration, a decision tree is added to the model, and it targets the residual errors of the earlier model. By aggregating weak learners sequentially, Gradient Boosting can construct a robust predictive model that is extremely effective at extracting intricate patterns from data. Careful regularization and parameter adjustment are necessary to avoid overfitting.

5.5 AdaBoost Regressor

AdaBoost, or Adaptive Boosting, combines several weak models to build a strong prediction model. Similar to Gradient Boosting, however, AdaBoost adapts weights of training instances on the basis of prediction error of past learners. Mispredicted instances receive larger weights, with the aim to force future models to pay particular attention to challenging cases. Training in a sequence enhances accuracy but potentially makes models more sensitive to noisy data and outliers.

5.6 XGBoost Regressor

XGBoost (Extreme Gradient Boosting) is an optimized and scalable implementation of the gradient boosting algorithm. It adds new features such as regularization, parallel computing, and tree pruning to improve performance and avoid overfitting. XGBoost develops an additive model in a forward stage-wise fashion where each additional tree tries to minimize a regularized objective function. The technique is renowned for being very fast and accurate in dealing with structured data.

5.7 Extra Trees Regressor

The Extra Trees (Extremely Randomized Trees) model is yet another tree-based ensemble method. It is quite similar to Random Forest but adds more randomness during the tree construction process by choosing cut-points at random for splitting features. This randomness tends to reduce overfitting and enhance model variance. Extra Trees work well with large datasets and are good at modeling non-linear relationships.

VI. MODEL EVALUATION

This research assesses the performance of different machine learning models for house price prediction based on both regression and classification metrics. Regression assessment was conducted based on Mean Absolute Error (MAE), Mean Squared Error (MSE), Root Mean Squared Error (RMSE), and R-squared (R^2) to measure prediction accuracy and sensitivity to error. In addition, the models were validated on a two-class classification problem with a price cut-off value to identify properties that are more than or less than 50 lakhs. For this, Accuracy, Precision, Recall, and F1 Score were utilized to gauge classification performance. The dual application of regression and classification metrics provides an overall evaluation of each model's predictive strength and classification correctness, facilitating the selection of the most appropriate model for implementation in real-world.

6.1 Accuracy Measure

In classification problems, it is essential to measure the performance of a model with strong and useful metrics. Of the most used are Precision, Accuracy, Recall, and F1 Score. These are all based on the confusion matrix, which includes the number of true positives (TP), false positives (FP), true negatives (TN), and false negatives (FN).

1. Accuracy

Accuracy is the proportion of correctly predicted instances (positive and negative) to the total number of predictions. It provides an overall measure of accuracy but can be deceptive if the dataset is unbalanced.

$$\text{Accuracy} = \frac{TP+TN}{TP+TN+FP+FN}$$

2. Precision

Precision, or the Positive Predictive Value, is the proportion of correctly predicted positive observations to the total predicted positives. It quantifies the model's capacity not to produce false positives.

$$\text{Precision} = \frac{TP}{TP+FP}$$

A high precision means that the model is committing very few false positive mistakes.

3. Recall

Recall, or Sensitivity or True Positive Rate, is the proportion of correctly predicted positive observations to all actual positives. It is a measure of the model's capacity to identify all the relevant cases (i.e., true positives).

$$\text{Recall} = \frac{TP}{TP+FN}$$

A high recall means that the model is picking up most of the actual positive instances with fewer false negatives.

4. F1 Score

The F1 Score is the harmonic mean of precision and recall. It is very useful when there is an imbalanced class distribution or when precision and recall are both significant to the problem.

$$\text{F1 Score} = 2 \times \frac{\text{Precision} \times \text{Recall}}{\text{Precision Recall}}$$

The F1 Score gives equal weightage to precision and recall and thus offers a balance between the two, making it a robust metric in cases where trade-offs are involved between false negatives and false positives.

Table 1: Comparison of Accuracy, Presicion, Recall and F1 score for different models

Model	Accuracy	Precision	Recall	F1 Score
Linear Regression	0.9012	0.9204	0.9501	0.9350
Decision Tree	0.8847	0.9046	0.9455	0.9246
Random Forest	0.8812	0.8870	0.9640	0.9239
Gradient Boosting	0.8301	0.8394	0.9557	0.8938
AdaBoost	0.7479	0.7479	1.0000	0.8558
XGBoost	08874	0.8872	0.9732	0.9282
Extra Trees	0.8198	0.8226	0.9677	0.8893
Neural Network	0.8108	0.8044	0.9871	0.8864

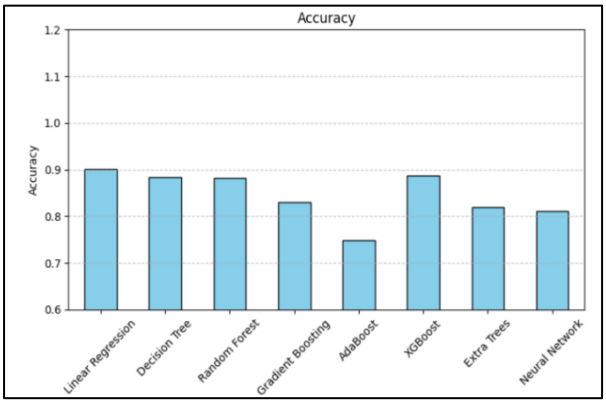

Fig 3: Accuracy Graph

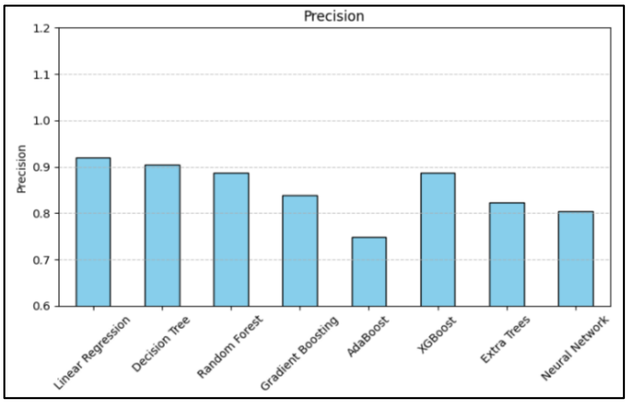

Fig 4: Precision Graph

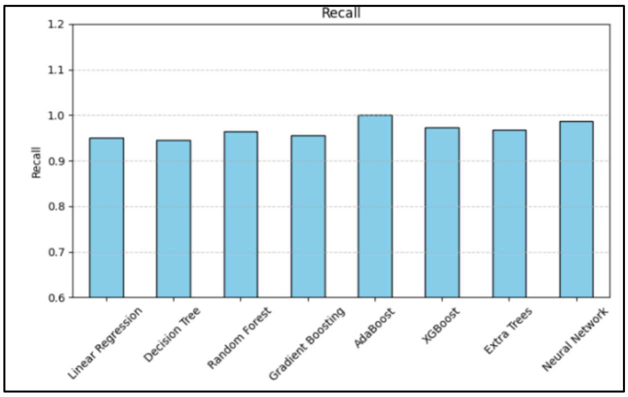

Fig 5: Recall Graph

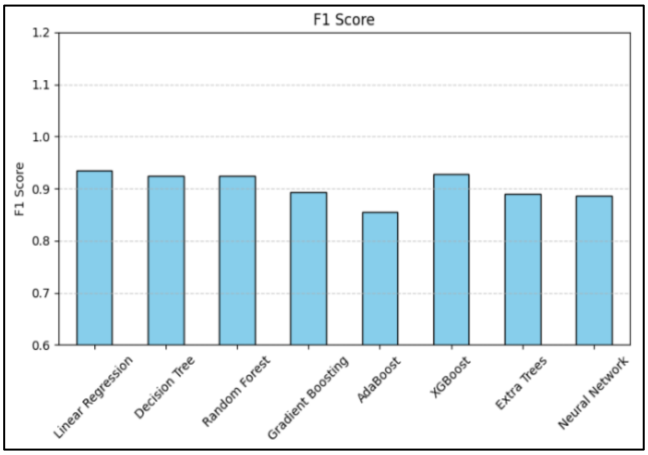

Fig 6: F1 Score Graph

6.2 Error Metric Measure

Mean Absolute Error (MAE) was utilized to compute the average magnitude of errors between predicted values and actual values, independent of their direction. It computes the absolute values of the differences between predicted and actual values and then takes the mean of these differences. Because MAE does not treat large errors differently from small errors, it provides a simple and straightforward measure of the extent to which the predictions may stray from actual values on average. This makes it particularly valuable for comparing models based on mean prediction error.

Mean Squared Error (MSE) was used to measure the average of the squared differences between observed and predicted values. Squaring the errors first and then taking their average, MSE places more emphasis on large errors. This makes MSE very sensitive to outliers and very suitable where extreme deviations from the observed value have to be penalized more. MSE is helpful in detecting whether the model makes extreme errors in certain instances.

Root Mean Squared Error (RMSE) was also taken into account in model assessment. RMSE is actually the square root of the MSE, and it gives an error measure of the same unit as that of the target variable (here, house prices). Due to squaring followed by square rooting, RMSE again penalizes large errors but is more interpretable in real-world sense. This metric is particularly valuable when stakeholders or users require insight into the performance of models in units that they are familiar with, like money.

R-squared Score (R^2) was an important metric that was utilized to comprehend how accurately each model accounted for variability in the target variable. R^2 provides a measure of the percentage of variation in the house price that is explained by the features fed into the model. A greater R^2, nearly 1, means the model fits the variability in the data, which is indicative of a good fit of the model. A low R^2 means the model does not fit significant patterns in the data. R^2 also provides information about how much improved the model is compared to a baseline that predicts the mean every time.

For every model comparison, the dataset was divided into a training and testing subset, with 80% of the data used for training and 20% for testing. This guaranteed that models learned from one subset of the data and were tested on data not seen before. This division was done to evaluate the model's generalization capacity and overfitting detection, a situation where a model can perform adequately on training data but inadequately on new data.

To further optimize model performance, GridSearchCV was employed for hyperparameter optimization. This entails specifying a grid of hyperparameter values and systematically testing all possible combinations with cross-validation. For each model, GridSearchCV assisted in determining the optimal parameter setting that resulted in the lowest error and highest predictive accuracy. This procedure was crucial in getting the best out of advanced models such as Random Forest, Gradient Boosting, XGBoost, and Neural Networks whose performance largely depends on the optimal selection of hyperparameters.

Summing up, a blend of several performance metrics, correct data splitting, and intensive hyperparameter tuning guaranteed thorough and reliable model evaluation. This multi-stage evaluation process permitted judicious selection of the best-performing model adequate for house price prediction in real-world applications.

Table 2: Comparison of Error metric measure for different models

Model	R^2 Score	MAE	MSE	RMSE
Linear Regression	0.8629	16.1554	711.0564	26.6656
Decision Tree Regressor	0.7060	19.8930	1524.7572	39.0481
Random Forest Regressor	0.7788	18.3787	1147.3619	33.8727
Gradient Boosting Regressor	0.8231	18.4790	917.8119	30.2954
AdaBoost Regressor	0.6231	30.5953	1954.8133	44.2133
XGBoost Regressor	0.8424	15.6530	817.2228	28.5871
Extra Tree Regressor	0.7818	19.7006	1131.5593	33.6387
Neural Network	0.8070	18.2572	1001.0283	31.6390

VII.RESULTS AND DISCUSSION

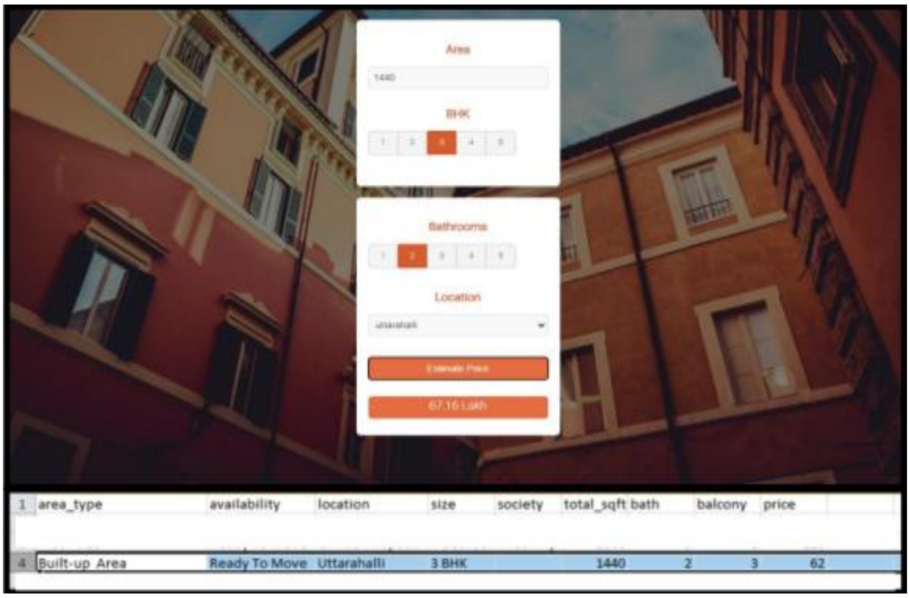

Fig 7: Result of our Project

The performance of the house price prediction system was validated with trial inputs via the front-end of the application. Important property characteristics such as total area, bedrooms (BHK), bathrooms, and location were entered by the user. For example, a trial input of 1550 square feet area, 3 BHK, 2 bathrooms, and the location "KR Puram" was entered via the interface.

When this input was given to the model, it forecasted the property price at 68.42 Lakh INR. This was contrasted with a comparable property from the dataset of the same area and room setup in KR Puram and labeled as "Ready to Move". The listed price for this comparable property turned out to be 65 Lakh INR. The relative closeness of the forecasted price to the actual price gives credence to the practical efficacy and applicability of the model.

To compare and measure model performance, several machine learning models were trained and tested based on common regression performance metrics: R^2 Score, Mean Absolute Error (MAE), Mean Squared Error (MSE), and Root Mean Squared Error (RMSE). These values enabled the determination of how accurately each model could predict housing prices and how closely predictions aligned with real values.

The Linear Regression model worked exceptionally well, yielding an R^2 Score of 0.8629, the best among all models, and a very low MAE of 16.15 and RMSE of 26.66, reflecting very high accuracy with comparatively small average errors. This simple model picked up the underlying trend in the data very well.

The Decision Tree Regressor performed relatively poorer, with an R^2 of 0.7060, a greater MAE of 19.89, and the largest RMSE of 39.04 of all models, indicating that it was an overfitting model or unable to generalize to unseen data points.

Random Forest had a slight edge over Decision Tree, with $R^2 = 0.7788$, MAE = 18.37, and RMSE = 33.87, indicating that ensemble techniques provided stability and reduced variance but still had scope for improvement.

Gradient Boosting provided a good trade-off with $R^2 = 0.8231$, MAE = 18.47, and RMSE = 30.29. The increase in RMSE over Random Forest suggests that boosting techniques were efficient in fine-tuning predictions.

The AdaBoost model had, however, the lowest R^2 of 0.6231, very high MAE at 30.59, as well as an RMSE at 44.21, marking poor performance at capturing intricate patterns and adding value to the global model comparison.

Conversely, XGBoost was among the best performing models with an R^2 Score of 0.8424, MAE of 15.65, and RMSE of 28.58. The model was able to keep par with Linear Regression when it came to low error measures while also embracing non-linear associations better, thus making it a good option.

Additional Trees Regressor gave moderate values of $R^2 = 0.7818$, MAE = 19.70, and RMSE = 33.63 with performance slightly superior to Random Forest but inferior to the boosting methods.

Lastly, the Neural Network model (MLPRegressor) also proved competitive with an R^2 value of 0.8070, MAE of 18.25, and RMSE of 31.63. Although not better than Linear Regression or XGBoost, it was still highly predictive, considering its capability to learn non-linear relationships in the data.

Comparative analysis proved Linear Regression and XGBoost as the top-performing algorithms with the most stable and accurate results in terms of accuracy as well as error minimization. Feature importance assessment from tree-based models highlighted the key role played by location, area of property, and bedrooms in predicting price. These observations further prove that taking these features into account dramatically increases prediction accuracy and supports their weightage in identifying property value.

In general, the model evaluation validated that although several models offered competitive performance, XGBoost and Linear Regression were the best balanced and accurate predictors of this house price prediction problem.

VIII. WEB APPLICATION DEVELOPMENT

A web application based on Flask was created to allow users to enter property information, including location, square meters, and bedrooms and bathrooms, in an attempt to get real-time property price predictions. The backend of the application had the trained model integrated into it, enabling the system to make proper predictions from the input data user entered. This integration provided for the dynamic generation of the predictions, making use of the model's ability to provide instant accurate results.

The frontend of the application was developed with HTML, CSS, and JavaScript to offer a user-friendly interface for smooth interaction. HTML was employed to organize the web pages, whereas CSS was utilized to design the application to make it an attractive and responsive interface. JavaScript was used to manage user interactions and enable real-time communication with the backend. The integration of these technologies created an easy and seamless user experience, where users were able to simply enter property details and receive price predictions without encountering any technical challenges. The app was made to be both useful and accessible, and property price prediction was made available to users across a broad spectrum.

IX. CONCLUSION AND FUTURE SCOPE

In this research, we investigated the use of machine learning methods for predicting housing prices, with emphasis on utilizing features like location, area, and number of bedrooms. The project showed that sophisticated models such as Random Forests and Gradient Boosting are superior to conventional methods such as Linear Regression in prediction accuracy. Through optimization of feature selection and hyper parameters, the models attained strong performance while being interpretable. The creation of a web application based on Flask further underscores the real-world applicability of the solution, where users can estimate housing prices in an interactive manner. While the success of this method proves significant, issues like outlier management and the inclusion of more socio-economic variables await future investigation. The contribution of this work is to the emerging domain of real estate analytics through a scalable, intuitive, and data-driven housing price estimation solution.

Investigate other features such as proximity to major landmarks, schools, hospitals, and public transportation. Integrate external information such as crime rates, levels of pollution, and municipal development plans to refine forecasts. Model Optimization. Host the model on cloud platforms such as AWS, Google Cloud, or Azure for improved scalability and performance. Employ containerization tools such as Docker and orchestration platforms such as Kubernetes to deploy and scale the application. Continuous Improvement Feedback Loop Establish systems to collect user feedback and refresh the model with fresh data from time to time. Implement retraining pipelines automatically to ensure the model is updated with the most recent trends.

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Easy Car Rental Management System

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ABSTRACT

Customers will be able to reserve their vehicles from anywhere in the world due to the Car Rental System. Consumers provide information to this application by filling in their personal information. When a consumer creates an account on the website, he or she can reserve a car. The proposed system is an online system that is fully integrated. It effectively and efficiently automates manual procedures. Customers are aided by this automated method, which allows them to fill in the specifics according to their needs. It contains information on the sort of car they want to hire as well as the location. The goal of this system is to create a website where customers can book their automobiles and request services from anywhere in the world. There are three phases to this car rental system mentioned in the introduction.

Keywords: Research Paper, Technical Writing, Science, Engineering and Technology

I. INTRODUCTION

The Car Rental Management System is designed to address the challenges faced by traditional car rental agencies, such as manual processing, paperwork, and inefficiencies in customer service. In an industry where customer satisfaction and operational efficiency are paramount, the need for a robust and automated solution has become increasingly evident. This system automates the entire rental process, from vehicle selection to payment, providing a user-friendly interface for both customers and administrators.

The traditional car rental process often involves cumbersome paperwork, long wait times, and a lack of real-time information regarding vehicle availability. These issues can lead to customer dissatisfaction and lost revenue for rental agencies. By leveraging technology, the Car Rental Management System aims to streamline these processes, reduce human error, and enhance the overall customer experience.

II. METHODS AND MATERIAL

A. USE CASE DIAGRAM

A Use Case Diagram is a visual representation that illustrates the interactions between users (actors) and a system to achieve specific goals. It outlines the series of events and actions that occur when an actor uses a system, showing the system's functionality and how users interact with it.

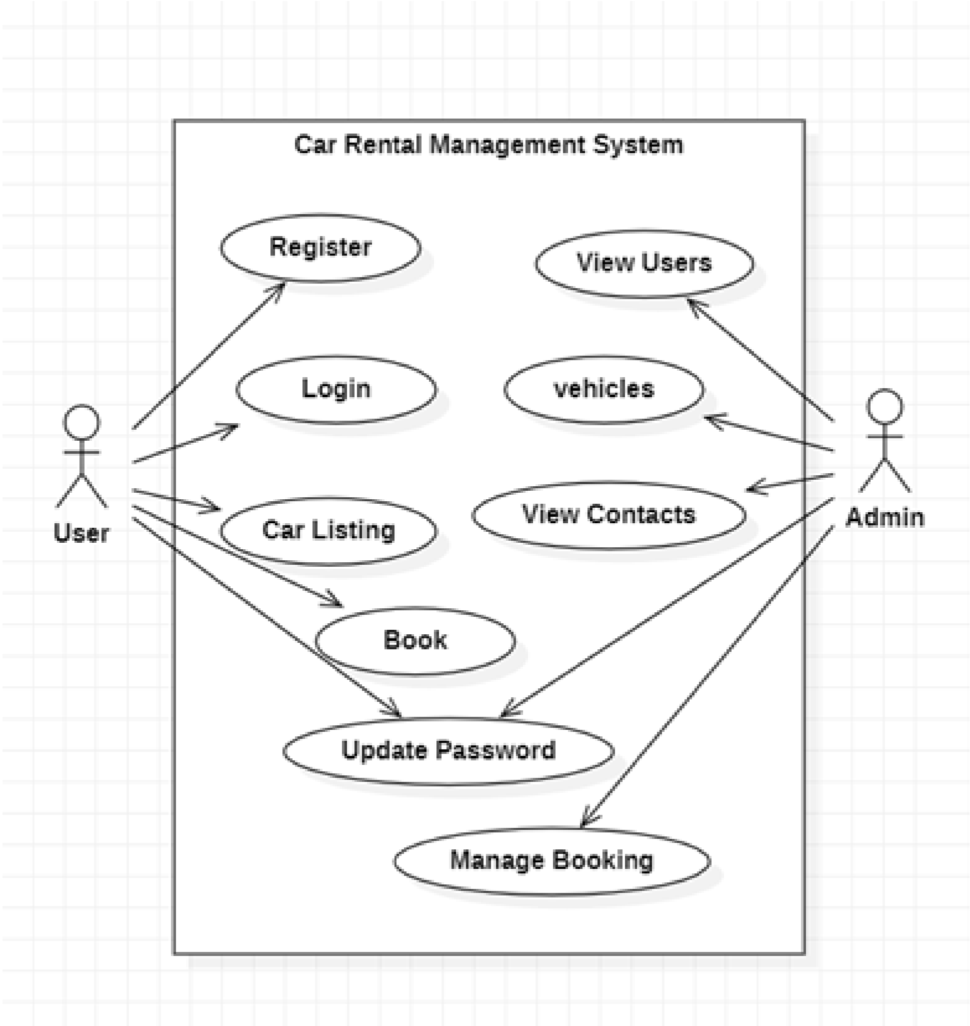

Fig 2.1: A use case diagram outlining the series of events and actions that occur when an actor uses a system.

B. DATA FLOW DIAGRAM

A Data Flow Diagram (DFD) is a graphical representation of the flow of information in a system. It illustrates how data moves through a system, who or what processes the data, and where it is stored. DFDs help to visualize the sequence of activities and the relationships between them, making it easier to understand how a system works.

Level 0, also known as the Context Diagram, presents the entire system as a single process, showing only its interactions with external entities.

Level 1 DFD then decomposes this single process into its major sub-processes, revealing the system's primary functional components.

It illustrates the data flow between these sub-processes, as well as their connections to external entities and initial data stores.

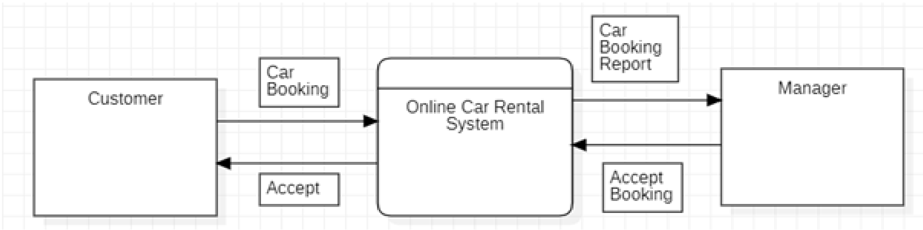

Fig 2.2: Level 0 DFD - Showing the entire system as one process and its data exchange with external entities, defining the system's scope.

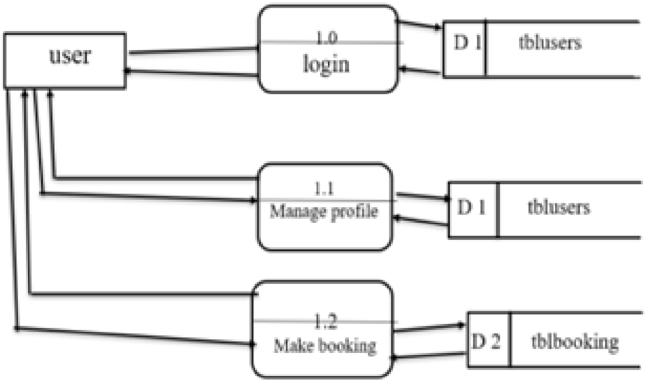

Fig 2.3: Level 1 DFD - A data flow diagram visualizing the sequence of activities and the relationships between them.

C. ENTITY RELATIONSHIP DIAGRAM

An Entity-Relationship Diagram (ERD) is a type of structural diagram used in database design. It illustrates the relationships between entities (things) in a database. ERDs help in visualizing and understanding how data is organized and connected, making them crucial for designing efficient and effective databases.

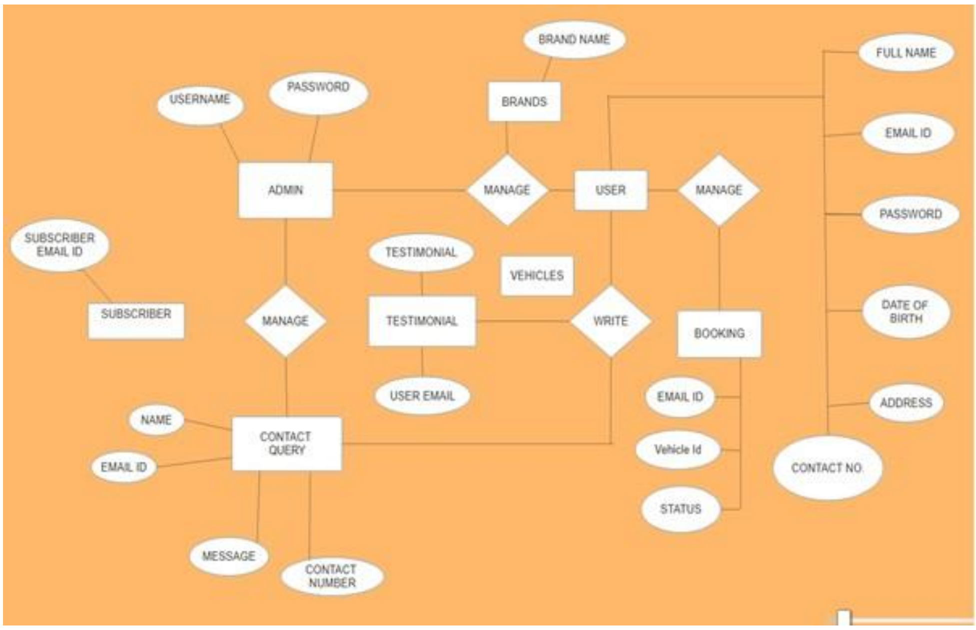

Fig 2.4: An entity relationship diagram visualizing and understanding how data is organized and connected.

III. RESULTS AND DISCUSSION

GRAPHICAL USER INTERFACE

Landing Page:

The CarEase landing page effectively presents its primary features: seamless car browsing, allowing users to explore a wide range of vehicles by type, brand, and price; easy booking and scheduling, eanbling quick reservations with flexible rental periods; andsecure payments, ensuring a smooth and trustworthy transaction process. The modern layout incorporates inituitive visuals and clear calls to action to highlight convenience, affordability, and reliability- motivating users to find book, and drive the car that fits their needs with confidence.

Fig 3.1: Visuals of the Landing Page

Admin Login Page:

The CarEase admin login page features a clean, intuitive interface with clearly labeled fields for username and password, ensuring quick and secure access for administrators. The background design combines sleek, automotive-inspired elements with professional, minimalistic visuals, creating a modern and authoritative feel. This layout is crafted to convey both reliability and efficiency, offering a secure entry point for admins to manage vehicle listings, bookings, and customer interactions with ease.

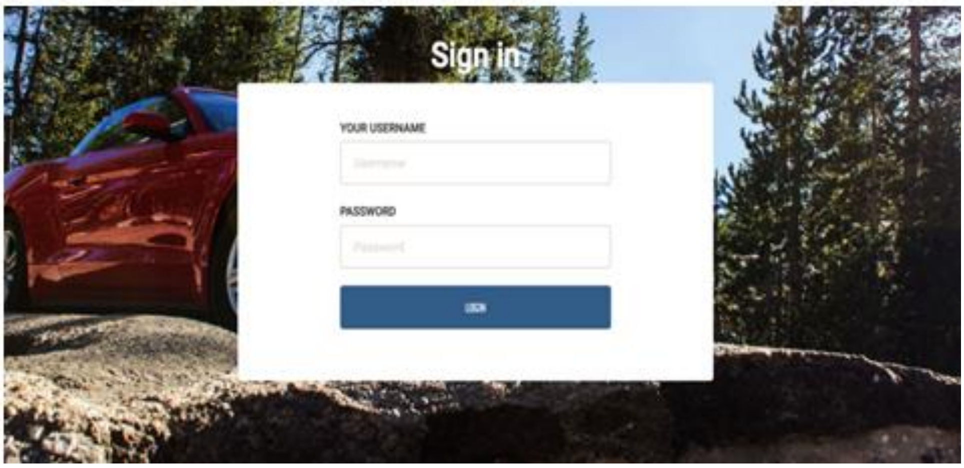

Fig 3.2: Visuals of the Admin Login Page

Login Page:

CarEase login page presents a sleek, user-friendly interface with clearly marked fields for username and password, ensuring smooth and secure access. The background features a clean, automotive-inspired design, possibly integrating subtle vehicle-themed visuals or dynamic gradients, creating an engaging yet professional atmosphere. This design approach is intended to convey trust, ease, and modernity, offering a welcoming and secure entry for users to quickly access their car rental options and manage bookings effortlessly.

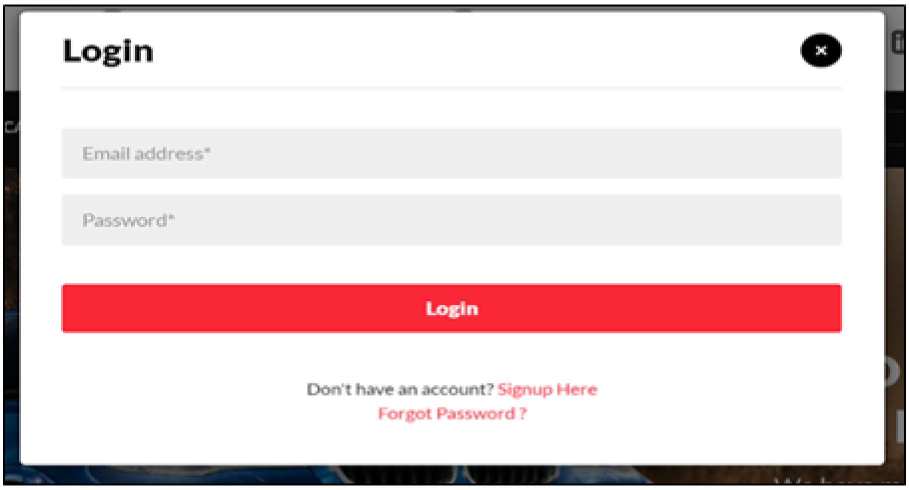

Fig 3.3: Visuals of the Login page.

Manage Vehicles:

The CarEase "Manage Vehicles" page provides a streamlined, user-friendly interface for administrators to efficiently oversee the car rental fleet. With a clean layout, admins can easily add, update, or remove vehicle listings, manage availability, and adjust pricing. The intuitive design allows for quick access to essential vehicle details such as model, specifications, and status, ensuring smooth and organized management of the rental inventory. This page offers a seamless, secure experience for admins to maintain and optimize the vehicle fleet.

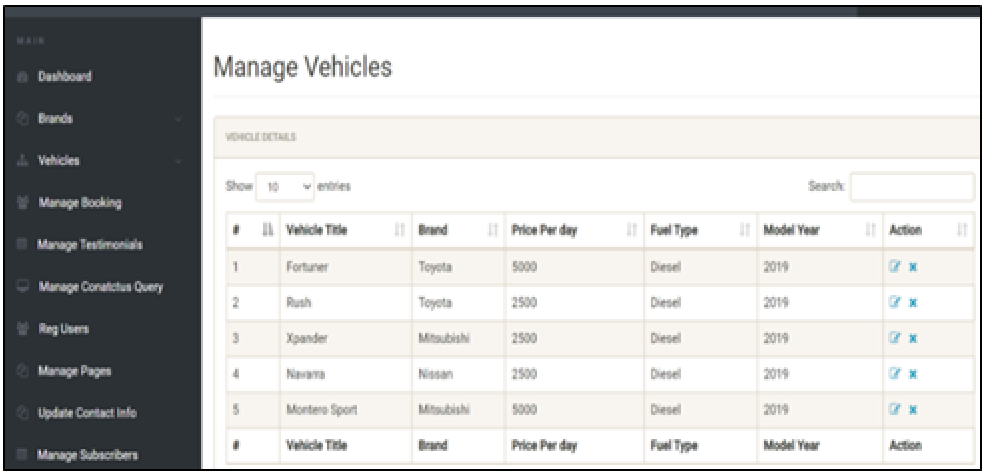

Fig 3.4: Visuals of the Manage Vehicles.

Add Brand:

The CarEase "Add Brand" page offers a straightforward, intuitive interface for administrators to easily add new car brands to the system. With a clean layout, admins can quickly input essential brand details, such as name, logo, and description, ensuring smooth brand management within the platform. The user-friendly design promotes efficient updates and ensures that the car rental fleet is organized by brand, allowing customers to browse and filter options based on their preferred manufacturers with ease.

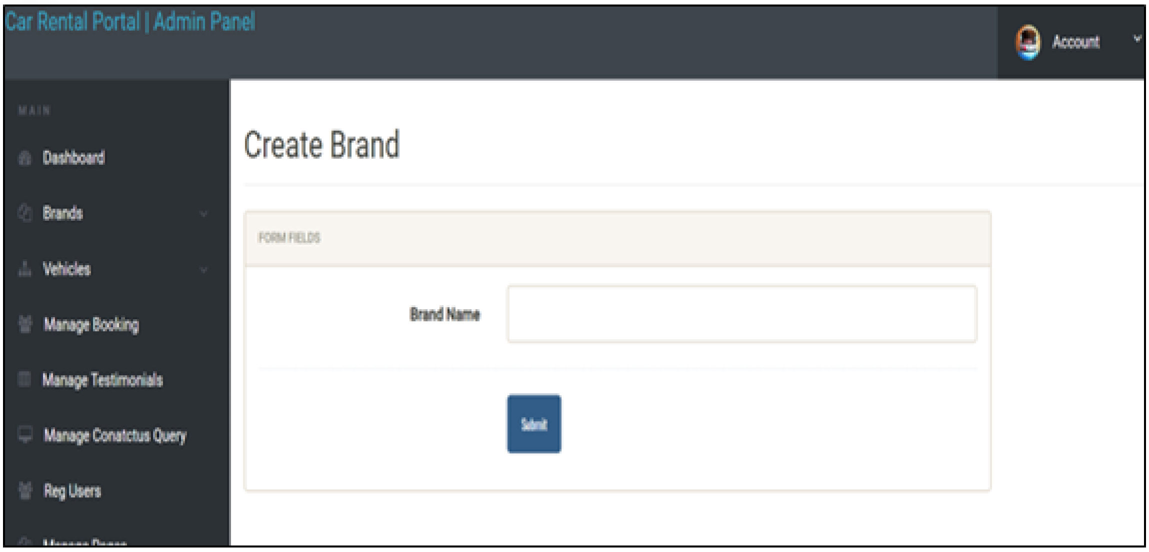

Fig 3.5: Visuals of the Add Brand.

IV. CONCLUSION

CarEase goes beyond the typical car rental platform, positioning itself as a comprehensive ecosystem designed to meet the evolving needs of modern vehicle renters and fleet managers. In an age where convenience, efficiency, and seamless user experience are paramount, CarEase offers a unified digital space where customers and administrators can engage effortlessly in a streamlined car rental process.

The platform fosters seamless communication through intuitive booking features and real-time availability tracking, ensuring that users can easily find the perfect vehicle when needed. Moreover, CarEase offers specialized tools for fleet management, enabling administrators to efficiently manage vehicle inventory, track rentals, and optimize pricing strategies, thus enhancing operational efficiency. CarEase also creates significant value for users seeking personalized rental experiences, offering tailored recommendations based on user preferences and rental history. With its easy-to-navigate interface, customers can quickly find, book, and manage their rentals, while also gaining access to flexible options such as short-term and long-term rentals, one-way trips, and more.

By blending networking opportunities, user-friendly booking systems, and efficient fleet management tools, CarEase empowers both customers and administrators to navigate the car rental process with ease and confidence. It serves as a modern solution to the challenges of vehicle accessibility, offering a reliable and dynamic space for both personal and business transportation needs.

V. ACKNOWLEDGEMENT

We would like to extend our heartfelt gratitude to the entire team behind CarEase for their vision and commitment in creating this innovative platform for car rental services. We also express our deepest appreciation to our mentor, **Dr. Soumitra Roy**, for his invaluable guidance and support throughout this project. His insights have been crucial in shaping our understanding of CarEase's potential and its role in transforming the car rental experience for customers and administrators alike.

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Micro Strip Multiplexor using Four Ultra-Wide Band BPF

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ABSTRACT

One quad band filter is proposed in this paper with a stub loaded open loop resonator. A design procedure to produce four BPFs is presented step by step. Lastly, a high-performance microstrip multiplexer is developed using the BPFs that were developed. When compared to earlier multiplexers, the developed multiplexer has the best insertion and return losses and the shortest dimensions. The frequencies at which it operates 2.2 GHz, 2.8 GHz, 3.5 GHz, and 4 GHz are suitable for multi-band Ultra-Wide Band (UWB) communications systems. The suggested quad-channel microstrip multiplexer is constructed and measured where a good agreement is obtained in order to validate the simulation and measurement results.

Keywords: Ultra-Wide Band, Microstrip Band Pass Filter, Insertion Los, Current density Distribution.

I. INTRODUCTION

Wide stopband microstrip devices, including filters, multiplexers, diplexers, and antennas, have become increasingly important in contemporary communication systems due to their small size [1–4]. Modern multi-service wireless communication systems have a high demand for microstrip multiplexers. They are lightweight, have a planar structure, and are easy to fabricate, among other benefits. For contemporary communication systems, a high-performance microstrip multiplexer with a smaller structure is more appealing. For the purpose of designing quad-channel multiplexers (quadruplexers) for RF communication systems, a variety of microstrip structures have been put forth [5–14]. However, the very broad implementation area is a drawback of the ideas that are shown in [5,14]. However, quadruplexers are more difficult to design than microstrip filters [15,16], dual-channel diplexers [17–19], and triplexers [20,21] because of their four channels. Furthermore, the quadruplexers that were introduced in [5-8] and [10-14] were unable to lower the insertion losses at every channel. In [5], a microstrip multiplexer for transceiver systems was designed using connected step impedance cells. It has two channels: one for the transmitter and one for the receiver. In [6], a four-channel microstrip multiplexer for international interoperability for microwave access (WiMAX) was created by coupling four semi-circular resonators.

Narrow channels with suppressed harmonics are features of this multiplexer. Four resonators and four channels have been integrated using a very large microstrip cell in [7]. The minor common port return loss at its channels is another drawback of this multiplexer. Like in [7], [8] integrates four straightforward open-loop rectangular resonators without any stubs using a very large junction circuit. In [9], a superconducting quadruplexer based on many spiral cells was created. Because of its extremely tight narrowband channels, it can be used in frequency division duplexing (FDD) applications. However, because it makes use of so many spiral cells, it takes up a lot of space. A quadruplexer with undesired common port return loss at all channels was achieved in [10] by using connected stub-loaded U-shaped resonators. Eight connected open-loops have been used in [11], increasing the size. A quadruplexer was achieved in [12] by using slot line stepped impedance stub-loaded resonators in the ground plane. Its poor pass band look and high losses are some of its drawbacks. Four resonators have been incorporated in [13] using a matching circuit made up of a series transmission line, an open-circuited transmission line, and a short-circuited transmission line. Nevertheless, it has undesirable losses at every channel, just like [12]. Although it has significant losses, the microstrip multiplexer described in [14] can attenuate the harmonics.
Large dimensions, low return loss, and high insertion loss are all issues that the suggested multiplexer is intended to address while maintaining a respectable level of channel isolation. Large patch cells load four connected loops in the proposed configuration.
While the third and fourth channels are geared to IEEE802.16WiMAX applications, having several channels makes it suitable for multi-service wireless networks.

II. PROPOSED OPEN-LOOP RESONATOR

Fig. 1a displays the basic BPF employed in this investigation. The suggested resonator, depicted in Fig. 1a, is used to create this BPF. The added BPF's frequency response is shown in Fig. 1b. This image illustrates the creation of a 3.3 GHz passband with an insertion loss of less than 1 dB and a return loss of about 20 dB. Fig. 2c displays the planned BPF's current density distribution. HFSS software is used to obtain Fig. 1c. The best parameters for the suggested BPF's frequency response are identified in Fig. 1c. It is evident that the BPF's frequency response is significantly impacted by the widths and lengths D1, D2, D3, D4, L1, L2, W1, W2, and S. Increasing the lengths and widths D1, L1, W1, and W2 causes the frequency response (S21) to shift to the left. Also, the frequency response (S21) is moved to the right by increasing the lengths and widths D2, D3, L2, and S. S21 is not significantly impacted by changing the length D3, however S11 is.

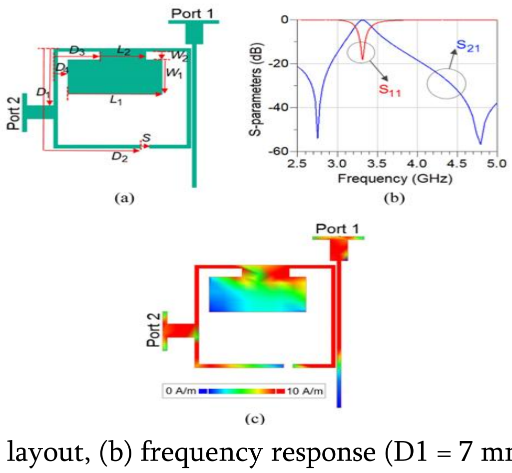

Fig. 1. Proposed BPF (a) layout, (b) frequency response (D1 = 7 mm, D2 = 19.52 mm, D3 = 4.3mm,D4=1.3mm,L1=8.8mm,L2=4.3mm,W1=4.2mm,W2=1mm,S=0.8mm) and (c) current distribution at 3.3 GHz.

III. DESIGN OF QUAD-CHANNEL MULTIPLEXER

The suggested 4 BPFs (which are shown in Fig. 2) are used to create a microstrip quad-channel multiplexer. The suggested multiplexer layout is shown in Fig. 3; all measurements are in millimeters. It is made up of four BPFs, including a stub-loaded open loop resonator, that are connected by a tiny matching circuit. The loop in each BPF is a resonator that is connected to a common port 1 to form a bandwidth channel. The internal tubing is broad and patchy, like the suggested BPF in Fig. 1a.Four resonance frequencies are obtained by differentiating the positions of internal stubs at each loop. A number of tiny capacitors in nF are produced by the coupling between the loops and port 1.To maximize the frequency response, these capacitors might increase the degree of freedom. We also used various optimization techniques to enhance the frequency responsiveness of the suggested multiplexor. The distribution of current density for the suggested multiplexer are displayed in Fig. 4.

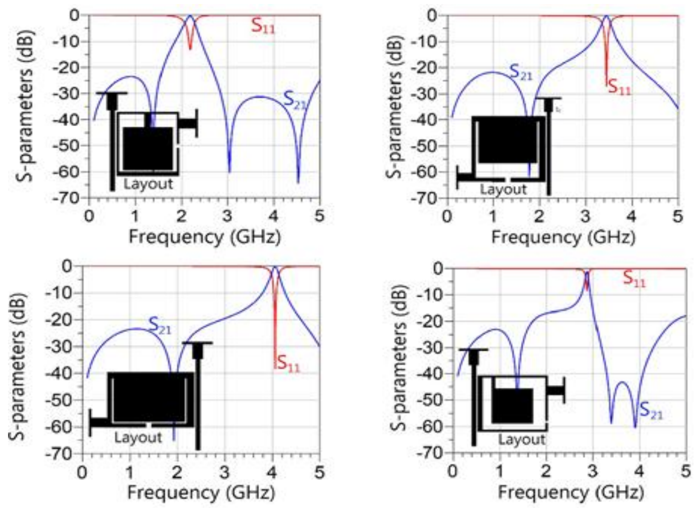

Fig.2. Layouts and simulation results of the obtained BPFs

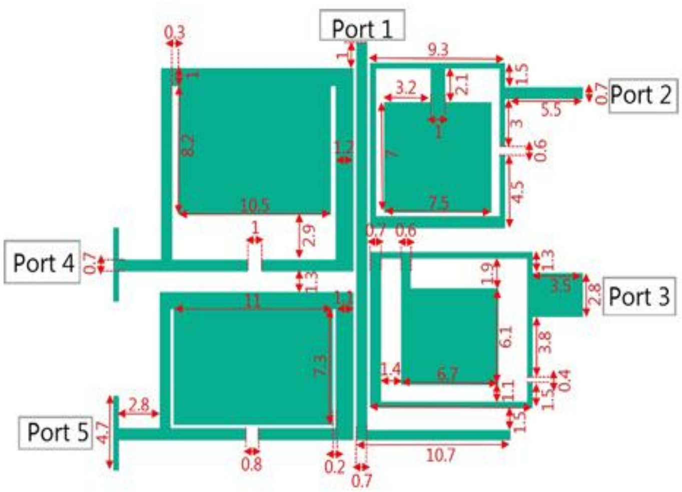

Fig.3. Layout and dimensions (in mm)of the proposed multiplexer.

The HFSS simulator simulates the suggested four-channel multiplexer. Arlon AD 250 substrate is used to manufacture the proposed multiplexer, The constructed structure has a very small area of 26.5 mm by 32.7 mm. With an Agilent Network Analyzer N5230A, the manufactured diplexer is measured.

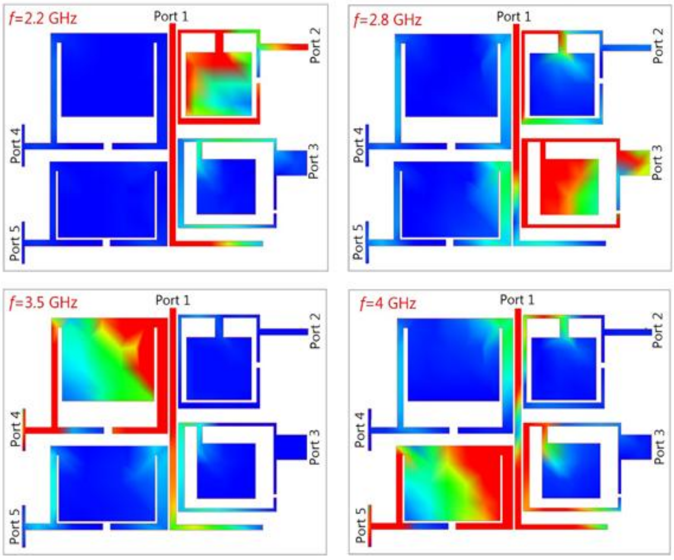

Fig.4. Current density distribution of the proposed multiplexer at its resonance frequencies.

A comparison of the simulated and observed S-parameters is shown in Fig.5. Our microstrip multiplexer operates at 2.2GHz, 2.8GHz, 3.5GHz, and 4GHz with simulated insertion losses of 0.14dB, 0.39dB, 0.21dB, and 0.27dB, respectively, according to the results. For the first, second, third, and fourth channels, the corresponding 3 dB cut-off frequencies are 2.08 GHz, 2.23 GHz, 2.80 GHz, 2.86 GHz, 3.40 GHz, 3.58 GHz, and 4.01 GHz, 4.18 GHz. Thus, the four FBWs% of the planned multiplexer are 6.9%, 2.1%, 5.1%, and 4.1%. At the first, second, third, and fourth resonance frequencies, the commonport return losses are 40 dB, 29 dB, 22 dB, and 32 dB, respectively.

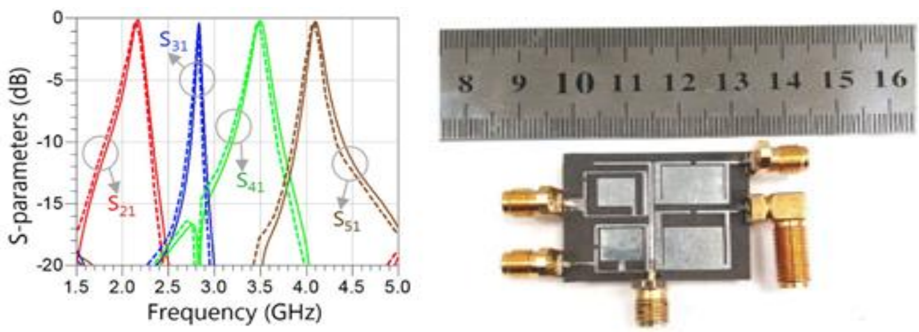

Fig.5. (a) Simulated (solid lines)and measured (dashed lines)S21,S31,S41,S51, (b) fabricated multiplexer.

IV. CONCLUSIONS

The proposed design of four novel microstrip bandpass filter (BPF) are combined to create a microstrip multiplexer with the best insertion and return losses and the shortest size. A revolutionary microstrip patch stub loaded open-loop resonator is included with every BPF. To learn more about the behaviour of the resonator, we examined the suggested resonator. We were able to enhance the BPF performance with the aid of the acquired data. Four channels at 2.2GHz, 2.8GHz, 3.5GHz, and 4GHz with low insertion losses of 0.14, 0.39, 0.21, and 0.27GHz, respectively, make up our proposed multiplexer. This multiplexer is the smallest and has the lowest injection losses.It is appropriate for multi-channel wireless communication systems since it has four channels spread across the radio frequency band.However, the third and fourth channels are suitable for WiMAX applications.

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IoT-Based Real-Time Baggage Tracking System with Fall Detection

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ABSTRACT

The rapid growth of the Internet of Things (IoT) has revolutionized various industries, including transportation and logistics, by enabling real-time monitoring and enhanced security features. This research paper presents an innovative IoT-based real-time baggage tracking system integrated with fall detection capabilities, utilizing the ESP32 microcontroller. The proposed system addresses common challenges in baggage handling, such as loss, theft, and damage, by providing continuous location tracking through GPS and GSM modules, while also incorporating an MPU6050 accelerometer-gyroscope sensor to detect falls or mishandling events. The ESP32 serves as the central processing unit, interfacing with IoT platforms to relay real-time data to users via a mobile application or web interface. Experimental results demonstrate the system's effectiveness in accurately tracking baggage and promptly notifying users of fall incidents, thereby improving security and user experience. This study highlights the potential of combining IoT technologies with low-cost hardware like the ESP32 to create scalable, efficient solutions for modern baggage management.

Keywords: Research Paper, Internet of Things (IoT), Fall Detection, Sensor Networks, Microcontroller, Wireless Communication (Wi-Fi, Bluetooth, LoRa), Real-Time Monitoring

I. INTRODUCTION

Falls among elderly individuals often result in significant health complications due to their reduced physical resilience. The most frequent consequence of a fall is a fracture; however, in more severe cases, injuries such as brain trauma, coma, or even paralysis may occur. In many instances, the impact sustained during the fall itself is the primary cause of harm. Delays in receiving medical attention can further aggravate the injuries, underscoring the importance of prompt emergency response to reduce potential health risks [1], [2].

Advancements in technology have opened up new opportunities to enhance elderly care. The development of low-power electronic components has enabled the creation of wearable health monitoring systems. Microelectromechanical systems (MEMS) sensors have streamlined the design and functionality of these systems. Additionally, location-based services (LBS) allow for real-time tracking, which is crucial in elderly care applications. Mobile computing has also facilitated the implementation of remote health monitoring solutions.

Various fall detection techniques have been explored and integrated into everyday applications [3]. One such approach relies on computer vision, where cameras placed within a specific area capture visual data to detect falls using image-processing algorithms. These methods can be further strengthened by incorporating external sensors, such as motion detectors [4]. A data fusion strategy can be employed to cross-validate the outputs from multiple subsystems, thereby enhancing the overall reliability of the fall detection system. Despite their effectiveness in indoor environments, the deployment of such camera-based systems outdoors is often limited due to practical constraints.

Sensor-based approaches, particularly those using motion sensors, are widely adopted as well. Devices such as accelerometers and gyroscopes can measure linear and rotational movements, which are critical for identifying falls. These methods vary based on the sensor configurations and the detection algorithms used. One basic method involves using a single triaxial accelerometer to capture three-axis acceleration data, which includes gravitational effects. When the sensor is worn on the body, filters such as low-pass or high-pass can be used to separate static and dynamic components of the motion signal [5]. Additionally, angular movement can be inferred by analyzing acceleration vectors and their resultant forces [6]. A more advanced method combines data from both accelerometers and gyroscopes, where the accelerometer captures translational motion and the gyroscope records angular velocity [7], offering a more comprehensive analysis of potential fall events.

II. SYSTEM DESIGN

The system architecture, illustrated in Figure 1, involves a wearable device positioned around the user's waist. This device continuously monitors motion data to identify potential fall events through acceleration analysis. Upon detecting a fall, it determines the user's current location using GPS. The system then transmits an alert message via the GSM network to designated caregivers, enabling a quick response to assist the individual in distress.

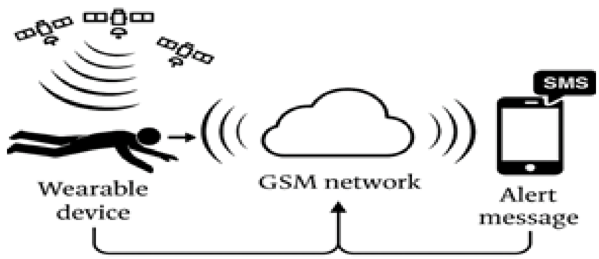

Figure 1 - System architecture.

III. FALL DETECTION ALGORITHM

3.1. Overview

The choice of recognition feature has decisive significance for successful fall detection. Information like linear movements (e.g., displacement, velocity, and acceleration) and angular movements (e.g., angle, angular velocity, and angular acceleration) could be obtained directly or indirectly. Besides these, frequency domain parameters could be extracted from basic sensor measurements by techniques such as FFT and wavelet [11, 12]. For single triaxial accelerometer application, accelerations and derived angular parameters could be used as recognition features.

The fall detection algorithm design is based on the choice of recognition features. According to the recognition feature, fall detection algorithms are classified as threshold-based and machine learning based. For threshold threshold-based method, the threshold of recognition feature is set by the designer before application, which makes the algorithm have a rapid response and less resource consumption [13]. But the choice of threshold needs both rigorous schemes and adequate experiments. For machine learning based design, the classification of fall and normal activities is available with the assistance of technologies such as support vector machine (SVM) and neural network [14, 15]. Machine learning assistance may enhance system robustness to some extent, but its algorithm design is always high computing resource consumed which limits its application in wearable device. As the compact wearable device requires low power consumption and a single triaxial accelerometer could provide effective information, threshold based fall detection algorithm will be used in this system.

3.2. Algorithm Design

The algorithm used in this fall alarm system is based on thresholds of the sum acceleration and rotation angle information. When a real fall happens, a collision between a human's body and the ground will produce an obvious peak value at the sum acceleration a, which has a magnitude as,

$$|a| = \sqrt{(a_x{}^2 + a_y{}^2 + aZ^2)} \qquad (1)$$

where ax, ay, and az present accelerometer measurements of three axes. The system uses the sum acceleration as the first step to distinguish high-intensity movements from others. But normal motions such as jumping or sitting also produce peak values, which means that additional detection features are required.

The second feature used here is an angle calculated based on acceleration measurements. As humans' motion has low acceleration, it is feasible to get the gravity component in each axis by using a low-pass filter. If gravity components could be separated before and after a human's fall, then it is possible to calculate the rotation angle of the accelerometer coordinate in 3D space, which is also equivalent to the rotation angle of the gravity vector relative to a fixed coordinate. The coordinate constructed by the accelerometer and the gravity vector is shown in Figure 2. The rotation of the gravity vector in fixed coordinates is shown in Figure 3.

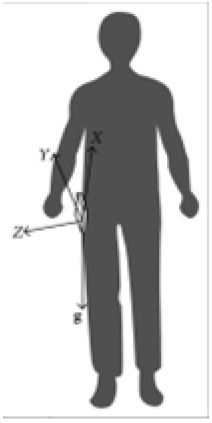

Figure 2 (a) *Coordinate and gravity before and after falling. (a) Before falling. (b) After falling.*

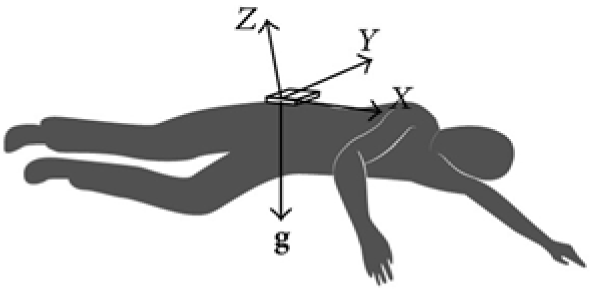

Figure 2 (b) *Coordinate and gravity before and after falling. (a) Before falling. (b) After falling.*

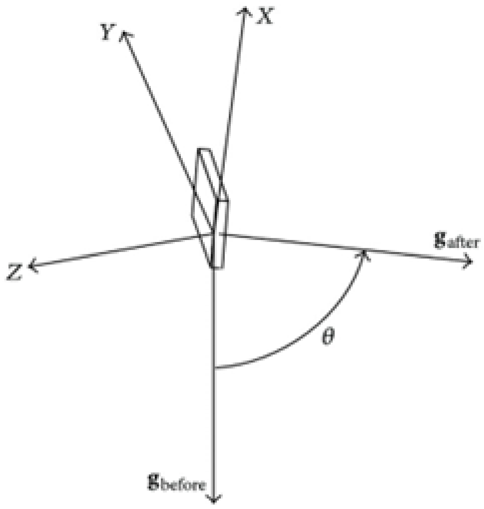

Figure 3 *Rotation of gravity relative to a fixed coordinate.*

Quaternion is an effective tool to describe rotation movement in human's gait change which also includes falling [16]. A quaternion could be described as

$Q = q_0 + q_1 \cdot \bar{i} + q_2 \cdot \bar{j} + q_3 \cdot \bar{k}$ (2)

which has magnitude as

$||Q|| = \sqrt{(q_0^2 + q_1^2 + q_2^2 + q_3^2)}$ (3)

Unit quaternion which has magnitude ‖Q‖ = 1 can be described as

$Q = \cos(\theta/2) + \sin(\theta/2) \cdot q_x \cdot \bar{i} + \sin(\theta/2) \cdot q_y \cdot \bar{j} + \sin(\theta/2) \cdot q_Z \cdot \bar{k}$ (4)

As shown in Figure 3, the rotation angle of Q equals θ. The rotation axis is orthogonal to the rotation plane and its direction is in accordance with right hand screw rule. qx, qy, and qz are three components of the unit vector which describe the orientation of the quaternion at the fixed coordinate.

Besides rotation movement, quaternion can also describe a vector in 3D space, such as the gravity vector g, which could be described as a quaternion

$g = 0 + g_x \cdot \bar{i} + g_y \cdot \bar{j} + g_z \cdot \bar{k}$ (5)

gx, gy, and gz are three components of g, which have a quaternion magnitude as

$||g|| = \sqrt{(g_x^2 + g_y^2 + gZ^2)} = g$ (6)

A unit quaternion Q is used to describe a human's falling movement, which can also be divided into three rotation quaternions Q1, Q2, and Q3 to simplify the calculation, as shown in Figure 4.

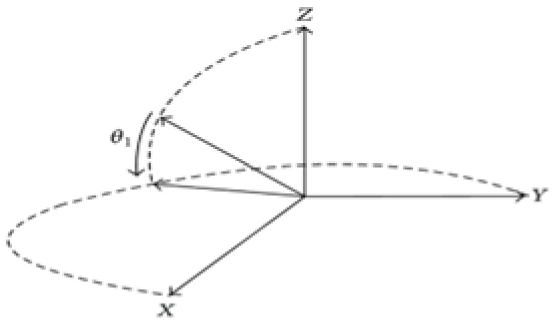

Figure 4 (a) *Decomposition of fall rotation quaternion Q. (a) Quaternion Q1. (b) Quaternion Q2. (c) Quaternion Q3.*

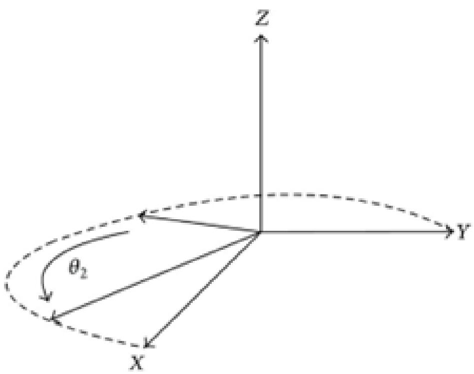

Figure 4 (b) *Decomposition of fall rotation quaternion Q. (a) Quaternion Q1. (b) Quaternion Q2. (c) Quaternion Q3.*

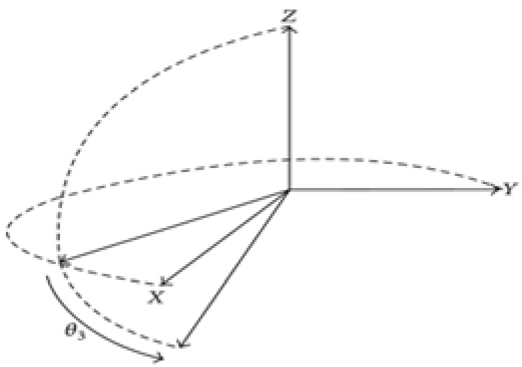

Figure 4 (c) *Decomposition of fall rotation quaternion Q. (a) Quaternion Q1. (b) Quaternion Q2. (c) Quaternion Q3.*

With the help of gravity vector information before and after a human's falling movement, as shown in Figure 3, these three separated quaternions are all available.

Q1 could be expressed as,

$Q_1 = \cos(\theta_1/2) + \sin(\theta_1/2) \cdot \sin(\alpha) \cdot \bar{i} + \sin(\theta_1/2) \cdot \cos(\alpha) \cdot \bar{j}$ (7)

which has rotation angle and rotation axis information as

$\theta_1 = \arctan(g_{before,Z} / \sqrt{(g^2_{before,x} + g^2_{before,y})})$

$\sin(\alpha) = (-g_{before,y}) / \sqrt{(g^2_{before,x} + g^2_{before,y})}$

$\cos(\alpha) = (g_{before,x}) / \sqrt{(g^2_{before,x} + g^2_{before,y})}$ (8)

Quaternion **Q2** can be calculated as

$Q_2 = \cos(\theta_2/2) + \sin(\theta_2/2)\cdot\bar{k}$ (9)

which has a rotation angle as

$\theta_2 = \arctan2(g_{after,y} / g_{after,x}) - \arctan2(g_{before,y} / g_{before,x})$ (10)

Quaternion **Q3** is

$Q_3 = \cos(\theta_3/2) + \sin(\theta_3/2) \sin\beta \cdot \hat{i} + \sin(\theta_3/2) \cos\beta \cdot \hat{j}$ (11)

with rotation angle and rotation axis information as

$\theta_3 = -\arctan(g_{after,z} / sqrt(g^2_{after,x} + g^2_{after,y}))$

$\sin\beta = -g_{after,y} / sqrt(g^2_{after,x} + g^2_{after,y})$

$\cos\beta = g_{after,x} / sqrt(g^2_{after,x} + g^2_{after,y})$ (12)

Then the rotation of the fall movement can be expressed by quaternion multiplication as

$g_{after} = Q \otimes g_{before} \otimes Q^*$

$= Q_3 \otimes Q_2 \otimes Q_1 \otimes g_{before} \otimes Q_1^* \otimes Q_2^* \otimes Q_3^*$ (13)

where $Q^* = q_0 - q_1\cdot\bar{i} - q_2\cdot\bar{j} - q_3\cdot\bar{k}$ is the conjugate quaternion of Q. Quaternion algebra is normally implemented based on basic matrix algebra [17]. Quaternion multiplication used above could be realized by matrix multiplication as

$$Q \otimes g_{before} = M(Q) \begin{bmatrix} 0 \\ g_{before,x} \\ g_{before,y} \\ g_{before,z} \end{bmatrix} = \begin{bmatrix} q_0 & -q_1 & -q_2 & -q_3 \\ q_1 & q_0 & -q_3 & q_2 \\ q_2 & q_3 & q_0 & -q_1 \\ q_3 & -q_2 & q_1 & q_0 \end{bmatrix} \begin{bmatrix} 0 \\ g_{before,x} \\ g_{before,y} \\ g_{before,z} \end{bmatrix} \quad (14)$$

The whole rotation quaternion can also be decomposed as

$Q = Q_3 \otimes Q_2 \otimes Q_1$

$= M(Q_3)\, M(Q_2)\, Q_1$ (15)

Q1, Q2, and Q3 are all available based on gravity information before and after the falling movement. At last, it is possible to get the four elements of quaternion Q by the equation above, and the rotation angle θ could be calculated as

$\theta = 2 \cdot \arctan(sqrt\ (q_1{}^2 + q_2{}^2 + q_3{}^2) / q_0)$ (16)

When an object is falling, the magnitude of θ will approach 90°, which is also a characteristic different from most normal activities. So it could be used as the second detection feature besides the sum acceleration.

The flow chart of the proposed algorithm is depicted in Figure 5.

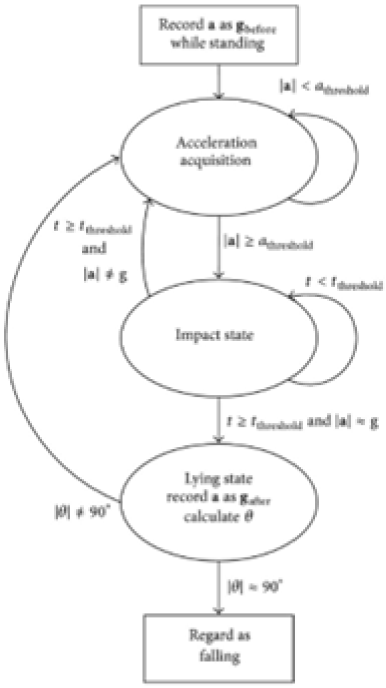

Figure 5 *Fall detection algorithm state machine.*

IV. IMPLEMENTATION

4.1. Hardware

ADI's digital triaxial accelerometer ADXL345 is the motion sensor used in this system. The GPS service and GSM communication function are integrated in SIMCom's SIM908 module. TI's 16-bit MCU MSP430F1611 is used to control the whole system and implement the detection algorithm [19].

The measurement range of the accelerometer could be set at ±2 g, ±4 g, ±8 g, or ±16 g, and the maximal sampling rate is 3.2 kHz. As human activities are normally at low frequency bands [20], 100 Hz is a proper sampling rate for human fall detection. There is an inner digital filter in ADXL345 that could weaken noise and reduce the burden of digital signal processing in the MCU to some extent. The measurements will be sent through the IIC (inter-integrated circuit) bus communication between the sensor and the MCU.

SIM908 can offer GPS and GSM service on serial port communication with the MCU, and it can also work in low-power mode.

Each hardware component of the wearable device is working under low voltage, and the detection algorithm does not need complex calculation resources, so the power consumption of the whole device is quite low. A 1200 mAh, 3.7 V polymer lithium battery is quite enough to provide the needs of the wearable device for a couple of days.

The hardware structure of the detection device is shown in Figure 6, and the PCB board prototype is shown in Figure 7.

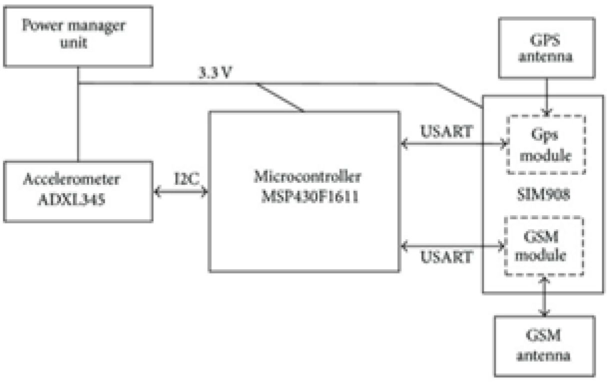

Figure 6 *Basic hardware structure.*

4.2. Software Implementation

The software design of the system can be divided into two parts. One of them is the software design in a wearable device, and the other is in the caregiver's handset.

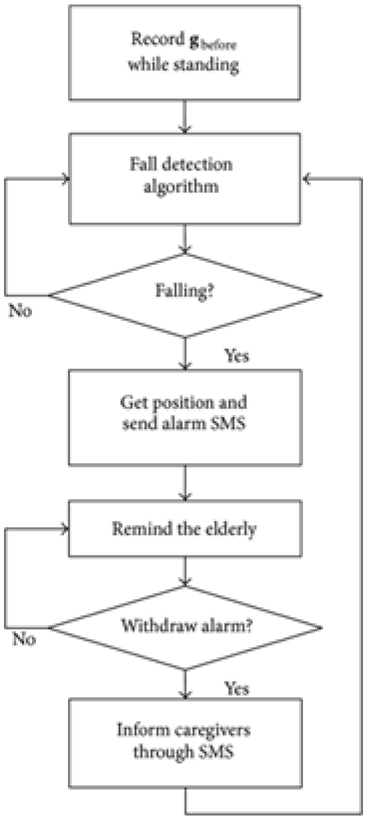

Figure 8 *System software flow diagram.*

After initialization of the system, g before would be extracted from acceleration measurements by using a low-pass filter when the elderly are standing. After that, the fall detection algorithm will be applied. If a fall has been detected, the wearable device will locate the user and send an alarm short message to caregivers immediately. Then the device will remind the elderly through vibration. If the user withdraws the alarm by pressing a button manually, the device will get back to the fall detection state, and a short message will be sent to inform the caregivers.

V. SYSTEM TEST

A system test of the fall detection system has been conducted based on the system design described above.

5.1. Wearable Device and Fall Detection Algorithm

The sampling rate of the accelerometer is set at 100 Hz, and the measurement range is ±16 g with a maximum precision of 4 mg. The MCU will read raw measurements from the sensor's inner FIFO and apply the detection algorithm.

The test objects are three different volunteers at the ages of 23, 42, and 60, respectively. Based on the analysis of these volunteers' experiment data, threshold and tthreshold are set as 2 g and 2 s, respectively. In order to get g when standing and lying after the fall, sum acceleration a, which has magnitude between (1 − 0.3) g and (1 + 0.3) g, will be considered as gbefore and gafter. Considering that the tilt of the ground or the lying posture of the elderly may affect the rotation angle, the rotation angle θ between (90 − 30)° and (90 + 30)° indicates that the elderly has fallen.

System test contains five kinds of activities of daily living (i.e., walking, jumping, squatting, sitting, and resting) and four kinds of falls (i.e., forward, backward, leftward, and rightward).

Each kind of motion has been repeated 20 times on each volunteer, and the detection results of the proposed algorithm and an acceleration threshold-based algorithm [13] are listed in Table 1.

Table 1. Test results for four kinds of falling and five kinds of ADL.

	Alarm times/test times	
Motion Type	*Proposed design*	*Acceleration threshold-based design*
Forward Fall	*60/60*	*59/60*
Backward Fall	*56/60*	*52/60*
Leftward Fall	*58/60*	*54/60*
Rightward Fall	*59/60*	*55/60*
Walking	*0/60*	*4/60*
Jumping	*0/60*	*11/60*
Squatting	*0/60*	*0/60*
Sitting	*0/60*	*9/60*
Resting	*5/60*	*10/60*

The sensitivity and specificity [21, 22] of the proposed system can be obtained from the test data in Table 1. Sensitivity of the proposed algorithm is 97.1%, and the specificity is 98.3%. Test results of the acceleration threshold-based algorithm show lower sensitivity and specificity at 91.6% and 88.7%, respectively.

VI. CONCLUSION

This paper developed a fall detection system based on a single triaxial accelerometer-based wearable device. There is no special requirement for the device's mounting orientation because the algorithm does not claim the axes of the accelerometer to be fixed strictly. The system has a low-power-consumption hardware design and a highly efficient algorithm, which could extend the service time of the wearable device. Both the hardware and software designs are suitable for wearable and outdoor applications.

As normal activity of resting also has a similar rotation as falling, it may trigger a fall alarm when the body hits the ground heavily. So the choice of a threshold is quite important to distinguish falling from heavily lying activity. A sufficient sample number collected from subjects of different ages and genders will improve the reliability and robustness of the threshold. Besides these, technologies such as SVM and neural networks are considered to seek out a proper classification method based on the features used in this system.

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Design and Implementation of a Smart Web-Based Car Rental Management System Using MERN Stack

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ABSTRACT

The Car Rental System enables customers to reserve vehicles from anywhere in the world. By creating an account and providing personal information, users can conveniently book cars through the platform. The system automates previously manual processes, making reservations faster and more efficient. Users can choose their preferred car type and pickup location based on individual needs. The primary goal is to provide a user-friendly, globally accessible platform for car rentals and related services.

This study presents the development and implementation of a comprehensive car rental management system using the MERN stack (MongoDB, Express.js, React.js, and Node.js), aimed at streamlining and enhancing the rental process for users and administrators. The system includes user login functionality, car listing features, reviews, and a driver registration module for individuals who wish to join the company as drivers. Stripe payment integration ensures secure and efficient transactions, while a Map API enhances the user experience by providing location-based services. The architecture of the system follows a modular and component-based approach, ensuring ease of maintenance, scalability, and reusability. React.js was utilized on the front end to create a responsive and interactive user interface, delivering a consistent and intuitive experience across a range of devices. The back end, powered by Node.js and Express.js, handles data processing, API communication, session management, and server-side logic. MongoDB, chosen for its document-oriented structure, serves as the database solution, offering the flexibility and scalability necessary for managing diverse data types including user profiles, vehicle listings, booking histories, payment transactions, and driver registrations. The system incorporates a wide array of features to address both user needs and business operations. Secure authentication mechanisms ensure that access to data and functionalities is appropriately managed according to user roles, including customers, administrators, and registered drivers. An advanced car search functionality allows users to filter available vehicles based on parameters such as location, price, car type, and transmission preferences, improving the efficiency and convenience of the booking process.

One of the critical components of the system is the integration of a secure payment gateway using the Stripe API, which facilitates real-time financial transactions while ensuring compliance with modern security and data protection standards. The inclusion of a Map API significantly enhances the user experience by offering interactive, location-aware services such as viewing pickup and drop-off points, estimating travel distances, and locating nearby available vehicles. To support users in understanding and navigating the platform effectively, a comprehensive user guide was developed. This guide provides detailed walkthroughs of system functionalities, account management procedures, booking processes, payment handling, and troubleshooting advice, thereby enhancing the usability and accessibility of the platform.

This project demonstrates the effective application of modern full-stack web technologies to solve real-world challenges within the car rental industry. By integrating responsive front-end development, robust server-side processing, secure financial transactions, and geolocation services, the system stands as a practical and scalable solution for vehicle rental management. The insights gained during this project serve as a valuable reference for future research and development efforts in similar domains, making this study a significant contribution to both academic and industry applications in web-based service systems.

Keywords: Car Rental Management System, Stack, Stripe Payment Integration, Map API, User Authentication, ICT, SOS.

I. INTRODUCTION

The digital age has transformed nearly every aspect of modern life, profoundly changing how people access and interact with services across various sectors, including retail, banking, healthcare, and education. One industry that has experienced significant advancement due to digitalization is the car rental sector. The integration of internet-based technologies has allowed this industry to evolve from its traditional, manual processes into a more efficient, streamlined, and user-centric digital experience.

Previously, car rentals involved a highly manual and time-consuming process. Customers were required to visit physical rental offices, stand in lines, fill out extensive paperwork, and wait for document verification before they could rent a vehicle. This process was not only inconvenient and frustrating for users—

particularly in fast-paced environments or during high-demand travel seasons—but also inefficient for businesses. Service providers faced operational challenges such as maintaining manual records, verifying customer information, tracking vehicle availability, and ensuring compliance with regulations. These procedures were susceptible to human errors, data mismanagement, and delays, ultimately resulting in poor customer experiences and reduced business efficiency.

The rise of advanced information and communication technologies (ICT), including high-speed internet, mobile applications, cloud computing, and integrated software systems, has enabled car rental companies to transition to fully digital platforms. These modern systems are designed to automate complex operations while enhancing customer experience and internal workflows. Web-based and mobile rental services now allow customers to access services within seconds, browse available vehicles, apply filters based on personal preferences, and view real-time availability and pricing across different locations. The digital interface also enables users to upload documentation, enter personal details, and make secure payments through integrated gateways—all from their smartphones or computers.

This shift toward automation and digitization has provided numerous benefits beyond convenience. For customers, modern platforms offer a host of value-added features, such as GPS-enabled tracking for real-time vehicle location, SOS services for emergencies, and mobile access to booking details. These tools contribute to transparency, safety, and improved service reliability. For rental agencies, integrated dashboards provide actionable insights into booking patterns, fleet usage, maintenance schedules, and customer behaviour, enabling data-driven decisions that boost operational efficiency and service quality.

Additionally, modern rental platforms often incorporate features such as digital signatures, automatic return reminders, demand-based dynamic pricing, loyalty rewards programs, and live customer support through chatbots or helpdesks. These enhancements personalize the rental experience, increase customer satisfaction, and foster long-term relationships between companies and clients.

One of the most significant advantages of digital transformation is scalability. Unlike traditional models that depend heavily on physical infrastructure and local staff, digital systems allow businesses to expand their operations across multiple cities or even internationally with minimal additional resources. This enables car rental companies—both startups and established enterprises—to reach wider markets, tap into new customer segments, and remain competitive in a technology-driven economy. The ability to serve a global, mobile, and tech-savvy audience positions digital platforms as critical tools for sustainable growth.

Moreover, digital transformation supports environmental sustainability by minimizing paper usage through digital transactions and encouraging the adoption of eco-friendly practices, such as smart fleet management and the promotion of electric or hybrid vehicles. These efforts not only align rental companies with global green initiatives but also appeal to environmentally conscious consumers.

In conclusion, the shift from manual car rental processes to sophisticated digital platforms has revolutionized the industry. These modern systems deliver greater efficiency, enhanced customer engagement. What was once a cumbersome and error-prone process has now become a seamless, data-driven, and customer-focused service.

II. LITERATURE REVIEW

The development and improvement of car rental systems have been explored in various studies, addressing a wide array of challenges, from enhancing user experiences to optimizing fleet operations. Several notable contributions have been made in areas such as technological advancements, user interface (UI) design, and operational optimization.

Waspodo, B., Aini, Q., & Nur, S. [1]. The research focuses on developing an online car rental system for Avis Indonesia. The system aims to streamline the rental process, where customers fill out forms to rent a car, and after verification, the car and driver details are provided along with rental history records. The system was developed using PHP 5.0 and MYSQL 5.1.30, following a five-stage development life cycle: planning, analysis, design, implementation, and use. The analysis showed that the system improved time efficiency by reducing the car delivery time by an average of two days and saved up to Rp. 750,000 in paper costs for rental history records. Thakur, A. (2021) [2]. The proposed Car Rental System is an online platform that allows customers worldwide to reserve vehicles by providing their personal information. Once customers create an account, they can book a car based on their preferences for type and location. This fully integrated system automates manual processes to efficiently assist customers in booking cars and requesting services. The system aims to provide a seamless experience where customers can access car rental services from anywhere globally. The introduction mentions three phases of development for this car rental system. Labroo, A., & Gupta, D. (2023) [3]. Automobile companies need efficient tools to manage their operations, including fleet management, customer handling, and reservations. The program we offer provides a solution for rental companies, helping them manage their vehicle inventory effectively. The software ensures that managers can easily add, edit, or delete cars in the fleet while maintaining accurate records of vital car details like make, model, year, and mileage. This improves decision-making and reduces time spent on manual tasks, such as paperwork, allowing more time to focus on providing better customer service. Chaudhary, V., Midha, S., & Bahuguna, R. (2024, January) [4]. This research aims to address the growing demand for online taxi booking through a web application and develop an information management system for the car rental industry. Currently, car rental bookings are manual, requiring significant time and effort. The system we propose, developed using PHP and MySQL, simplifies the process, making it more customer-friendly and reducing the time and effort involved in booking a car. The system allows users to lease cars remotely, manage their bookings, and update their profiles. It also enables administrators to update, delete, or retrieve vehicle information as needed.

Ogbiti, J. T., & Aaron, W. (2024). Development of a web-based car rental management system. Science World Journal, 19(3), 797-807[5]. This study focuses on the development and implementation of a car rental management system designed to improve the rental process for both users and administrators. The system was built using PHP, JavaScript, and Bootstrap, with a database managed by Microsoft SQL Server Express. Testing was performed using the MSUnit framework, achieving a 100% pass rate across all test cases, ensuring system reliability. A user guide was created to assist users in navigating the system. Overall, the project successfully demonstrates the effective use of modern technologies to create a robust and user-friendly car rental management system. Ganeshkar, V., Moze, A., Surwade, S., & Sonawane, S. An Online Car Rental Management System [6]. This online car rental system allows users to browse car listings, view features, and rent cars through credit card payment. Users must register with personal details and log in to access the system. After logging in, users can select cars, add them to the shopping cart, and make payments. The system also features a blog section where registered users can post and view blogs. Abayon, C. L. A., Peria, M. V. S., Requirme, J. R. D., Varona, K. S. B., & Villegas, J. C. (2023) [7]. This article proposes a web-based car rental system to address the challenges of manual booking. It aims to help car owners manage their rental business efficiently while providing customers with an easy booking process. The system ensures car owners can track customer data, reducing risks like accidents or theft. For customers, it guarantees their rights by offering preferred cars, fair prices, and well-maintained vehicles, particularly beneficial for areas with limited public transport or tourists.

Oliveira, B. B., Carravilla, M. A., & Oliveira, J. F. (2017) [8]. The Car Rental Management System automates the manual property trading process, improving services, record-keeping, data integrity, and security while creating a paperless environment. Users log in with email and password for secure access. Clients can make contact, check status, or provide feedback, while service providers manage orders and staff track records. Developed using Laravel 6.x, HTML5, CSS, Bootstrap 4, SQL, PHP 7.x, and JavaScript, the system streamlines event planning and client order fulfillment.

III. METHODOLOGIES

The prototyping methodology was selected to develop the car rental management system. Prototyping involves creating an initial version of the system, known as a prototype, which is then presented to stakeholders for feedback. This feedback is used to refine the prototype iteratively until it meets user requirements and expectations.

The key reasons for adopting this methodology are:

i. Active Stakeholder Involvement: Stakeholders are involved throughout the development process, providing continuous feedback.
ii. Early Detection of Errors: Errors and missing functionalities are identified and addressed early in the development cycle.
iii. Improved User Understanding: Stakeholders gain a clear understanding of the system's functionality and usability early in the process.

The prototyping methodology comprises six phases:

i. Gathering: Collecting detailed requirements from stakeholders through interviews and questionnaires.
ii. Initial Design: Creating an initial system design based on gathered requirements.
iii. Building the Prototype: Developing a functional prototype that demonstrates the key features of the system.
iv. User Evaluation: Presenting the prototype to stakeholders for feedback.
v. Refinement: Modifying the prototype based on stakeholder feedback.
vi. Final System Development: Develop the final system once the prototype is accepted.

A. System Architecture

The system architecture of the car rental platform is a robust and scalable solution built using the MERN stack, which comprises MongoDB, Express.js, React.js, and Node.js. These technologies synergize to create a full-stack development environment capable of handling high traffic, dynamic data, and real-time interactions. Below is an in-depth look at how each component of the stack contributes to the system:

➢ *MongoDB: The Database Layer*

MongoDB serves as the database for the car rental platform, offering a flexible and scalable solution for managing data. Its NoSQL document-based structure stores data in a JSON-like format, making it ideal for handling various types of data dynamically. Key advantages include:

i. Schema Flexibility: MongoDB allows dynamic schema design, enabling the system to handle diverse and evolving data types, such as:

- Car details (e.g., make, model, availability, and pricing).
- User profiles (e.g., personal details, preferences, and rental history).
- Transaction records (e.g., payments, bookings, and invoices).

ii. Scalability: As the platform grows, MongoDB can scale horizontally by distributing data across multiple servers, ensuring high availability and performance.

iii. Real-Time Capabilities: MongoDB integrates seamlessly with Node.js to handle real-time updates, such as tracking car availability or processing new bookings.

iv. Indexing and Querying: It supports advanced indexing techniques, ensuring that searches (e.g., finding cars based on filters like location or price) are fast and efficient.

➢ *Express.js: The Back-End Framework*

Express.js acts as the backbone of the application's server-side functionality. Running on Node.js, it simplifies the creation of APIs and handles key back-end operations, such as:

i. Routing: Express.js maps incoming HTTP requests to the appropriate back-end logic. For example:
   - A GET request retrieves available cars.
   - A POST request facilitates booking a car.

ii. Middleware Integration: Middleware in Express.js allows tasks such as:
   - Authentication (e.g., validating user credentials during login).
   - Logging requests for debugging.
   - Handling errors gracefully to enhance user experience.

iii. Data Management: Express.js acts as the intermediary between the front end and MongoDB, ensuring seamless data flow. For instance:
   - Fetching car details for display on the frontend.
   - Updating the database when a booking is made.

iv. Security: Express.js incorporates security practices such as using helmet to prevent common vulnerabilities and implementing JSON Web Tokens (JWT) for secure user authentication.

➢ *Node.js: The Server-Side Environment*

Node.js is the runtime environment powering the back end. It's known for its ability to handle high concurrency with efficiency and reliability. Here's how it contributes:

i. Asynchronous Programming: Node.js supports non-blocking I/O operations, enabling the platform to process multiple requests simultaneously. This ensures:
   - Faster response times, even during high traffic.
   - Smooth handling of real-time features, such as updating car availability in real time.

ii. Scalability: With its event-driven architecture, Node.js efficiently manages thousands of simultaneous connections, making it suitable for a car rental platform with growing demand.

iii. Integration with MongoDB: Node.js seamlessly connects with MongoDB using libraries like Mongoose, allowing developers to define data schemas and interact with the database intuitively.

iv. Modular Codebase: Node.js encourages modular development, enabling developers to divide functionality into reusable modules, such as:
   - User authentication.
   - Payment gateway integration.
   - API handling for car search and booking.

➢ *React.js: The Front-End Framework*

React.js is the user interface (UI) development library that powers the platform's front end, offering an intuitive and interactive user experience. Key benefits include:

i. Component-Based Architecture: React allows the application to be divided into reusable components, such as: Navigation bar, Car listing card, Booking form. This modularity simplifies development and enhances maintainability.

ii. Dynamic and Interactive UI: The Virtual DOM in React optimizes updates to the user interface, ensuring a smooth experience even as the application grows. Examples: Real-time car availability updates, Live search functionality for finding cars based on filters like location, price, or model

iii. State Management: React states management capabilities, combined with libraries like Redux or Context API, enable efficient handling of dynamic data such as: User preferences, Active bookings, Notifications and alerts.

iv. Responsive Design: o Using CSS frameworks like Tailwind CSS or Bootstrap, React ensures the platform is fully responsive, providing optimal experience on desktops, tablets, and mobile devices.

v. Integration with Back End: o React communicates with the back end via APIs, enabling seamless data exchange. For example: Fetching user booking history from MongoDB, Submitting new car rental requests.

MERN stack's technologies work together to build a powerful, scalable, and efficient car rental platform. MongoDB ensures flexible and scalable data storage, Express.js handles robust back-end operations, Node.js provides high performance server-side processing, and React.js delivers a responsive and dynamic user experience. This architecture ensures the platform can cater to growing user demands while maintaining reliability and performance.

B. Design

Dataflow Diagram provides an overall architectural view of the system, showing the flow of data between the server, user, drivers, web, and external entities.

i. Dataflow Diagram Level 0:

This diagram provides an overall view of the system, showing the flow of data between the customer, system, and external entities, shown in *Figure 1*.

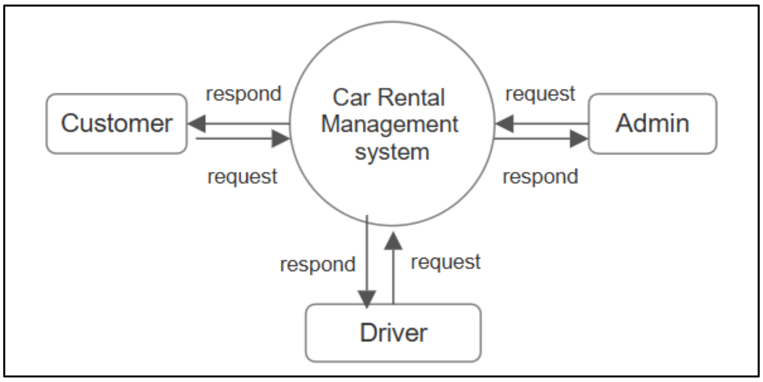

Figure 1. DFD Level 0

ii. Dataflow Diagram Level 1:

This diagram provides an overall view of the system, showing the flow of data between the customer, system, and external entities, shown in *Figure 2*.

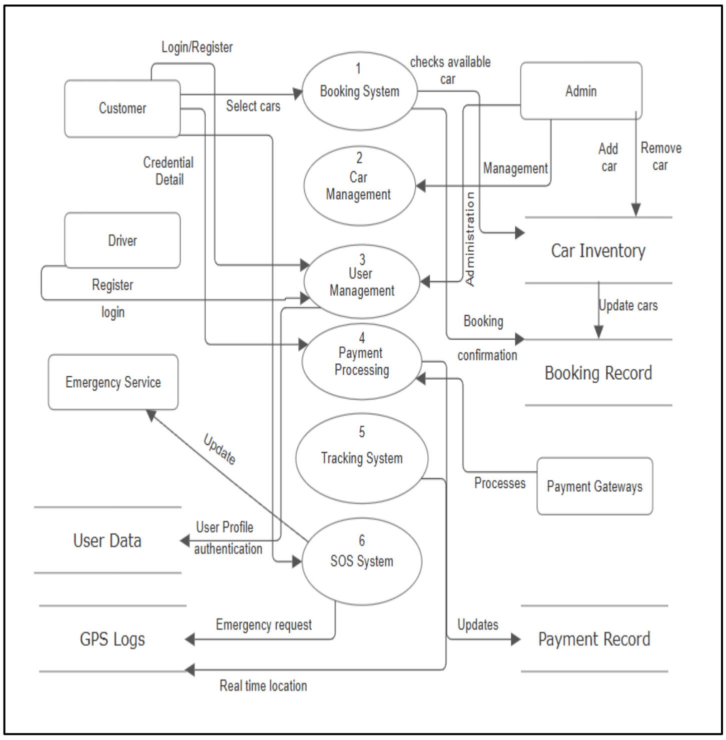

Figure 2. DFD Level 1

iii. Dataflow Diagram Level 2:

This diagram breaks down the system into major processes, data stores, and data flows, illustrating how information moves through the system as shown in *Figure 3*.

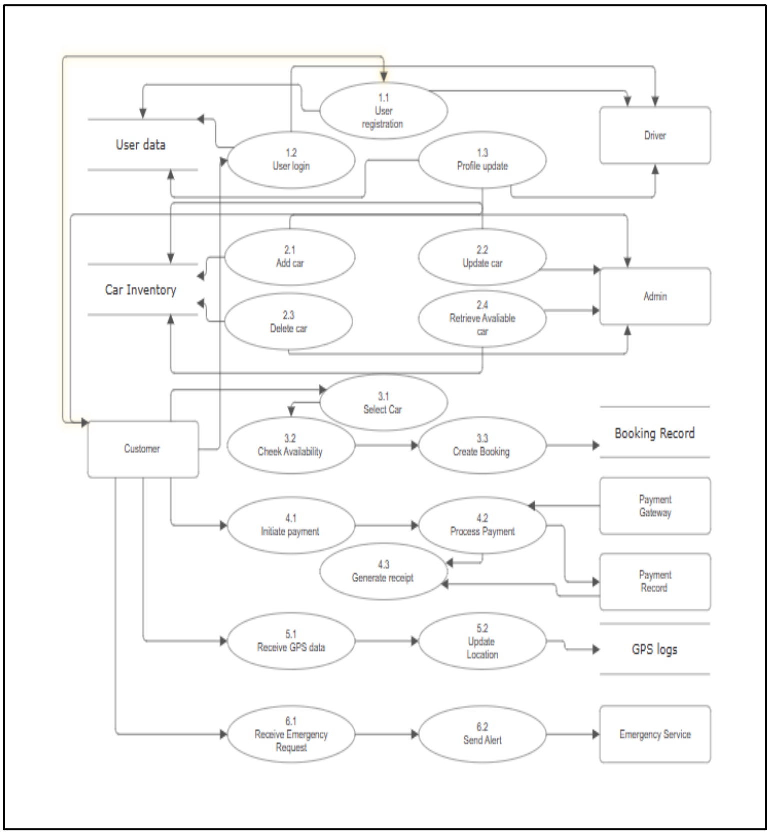

Figure 3. DFD Level 2

C. Implementation

The car rental system was developed using a modern technology stack to deliver a seamless and efficient user experience. The front-end was built using React.js, enabling a dynamic, component-based architecture. React's efficient UI rendering ensured that features like car listings, detailed car views, booking forms, and the user dashboard were responsive and interactive. The front-end utilized HTML for structure, CSS for design, and Bootstrap to enhance responsiveness across various devices. JavaScript added interactivity, allowing dynamic content updates such as filtering cars based on user preferences and performing client-side validation for booking forms. On the back-end, Node.js was used for its asynchronous, non-blocking nature, enabling the system to handle multiple concurrent requests efficiently. Key backend functionalities included user management, car data operations, and integration with external services. User authentication was implemented using Clerk, a modern authentication service, ensuring secure login, registration, and session management without compromising user data. For data storage, the system employed MongoDB, a NoSQL database, to manage car details, user information, and transaction data. MongoDB's flexible schema supported easy scalability, accommodating new features and data types. Payment processing was securely handled through integration with Stripe, ensuring seamless and secure transactions. The system features real-time tracking, implemented using Leaflet, an open-source mapping library. This allows users and administrators to monitor the live location of vehicles, enhancing transparency and improving fleet management. Additionally, an SOS feature was included to prioritize user safety, enabling customers to send immediate alerts with their real-time location to be designated contacts or authorities in emergencies. Overall, the system was designed to provide an intuitive, responsive, and secure car rental experience. Each feature was rigorously tested, ensuring smooth functionality and reliability throughout the platform

IV. RESULTS AND DISCUSSION

This research provides a detailed account of the implementation and testing of the car rental system, highlighting the technologies and tools used, including React.js for the front-end, Node.js and Express.js for the backend, MongoDB for data storage, and Stripe for secure payment processing. The system was designed to address the inefficiencies of traditional manual car rental systems by offering a scalable, user-friendly platform. The research also discusses the challenges faced during development, such as securing user data, integrating third-party services, and ensuring system scalability. The system incorporates real-time tracking using Leaflet, an open-source library for interactive maps. This feature enables users and administrators to monitor the live location of vehicles, ensuring better transparency, safety, and fleet management. Additionally, an SOS feature is implemented to prioritize customer safety, allowing users to quickly send alerts during emergencies by providing their real-time location to designated contacts or authorities. These features enhance the overall functionality and usability of the system while addressing critical safety and transparency concerns. Solutions were implemented to tackle development challenges, including robust security measures to protect user data, careful integration of third-party services like Stripe for secure payments, and scalable database management for handling growing user demands. The testing phase is thoroughly documented, including the development of test plans, a traceability matrix to ensure all requirements were met, and a test report summary that demonstrates the system's reliability and functionality.

A. Testing and Validation

Comprehensive testing was performed to ensure the car rental system's functionality, security, and user experience met the defined requirements. User authentication using Clerk was thoroughly tested for secure registration, login, and session management, ensuring that edge cases, such as expired tokens, were handled properly. The Stripe payment integration was rigorously tested to guarantee smooth and secure transactions, including error scenarios and compliance with security standards. The real-time tracking feature using Leaflet was tested to ensure accurate vehicle location displays and seamless tracking functionality. The SOS feature was also tested for its ability to send location-based alerts and provide an effective response in emergencies.

i. Homepage: When visitors to the website, be they customers, users, or anyone else with an interest, this is the first page that loads. Based on the customer's desired location inside the website, the page contains all the connections needed for them to move between pages as shown in *Fig 4.*

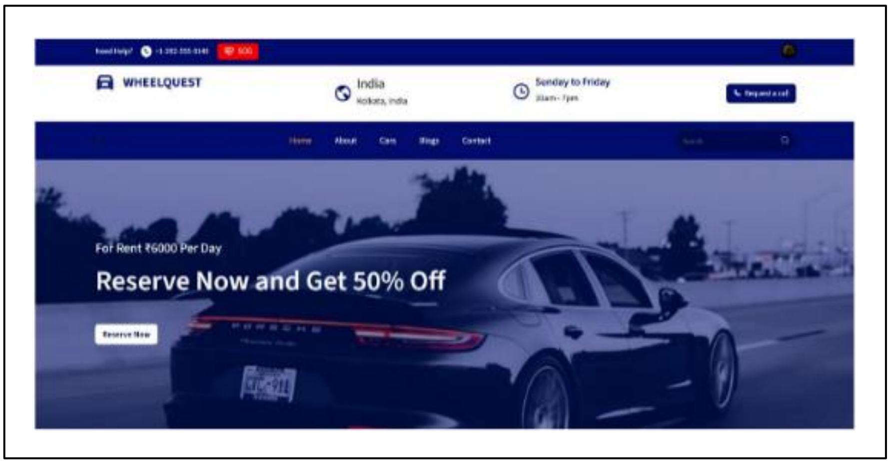

Figure 4. Proposed work Homepage

ii. Login and Registration page: The login form, which users can access by accurately entering their user credentials on, is located on the system login page, which is the initial page that appears to users upon accessing the website, as shown in *Fig 5.*

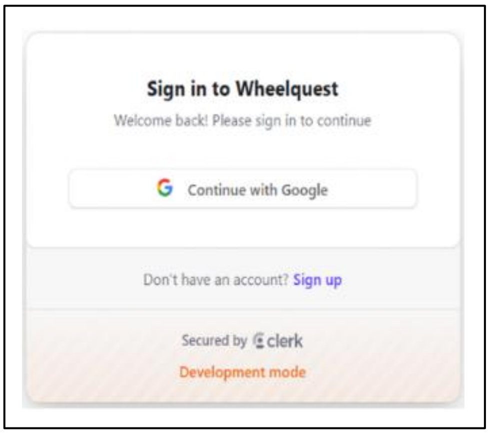

Figure 5. Project Login page

iii. SOS button: The SOS page is designed to prioritize user safety by providing a quick way to alert emergency contacts or authorities in case of an emergency. It allows users to send real-time location details with a single click, ensuring immediate assistance. The page also includes clear instructions and options for users to connect with emergency services directly, as shown in *Fig 6.*

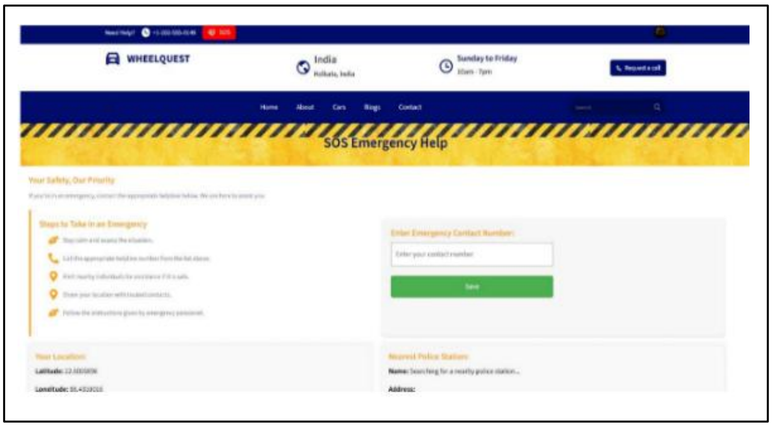

Figure 6. Work proposal SOS page

iv. Booking Page: This is the page that opens after clicking on the booking link as the customer tries to book or reserve a taxi. It appears in the form of a form in which the customer provides his / her details, as shown in *Fig 7.*

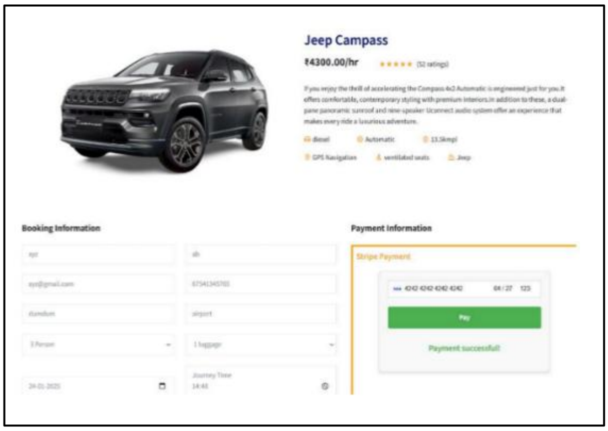

Figure 7. Car Booking page of the project

v. Car Listing page: The car listing feature displays a comprehensive catalogue of available vehicles, including key details like make, model, price, and availability. Users can filter the listings based on various criteria, making it easier to find a suitable car, as shown in *Fig 8.*

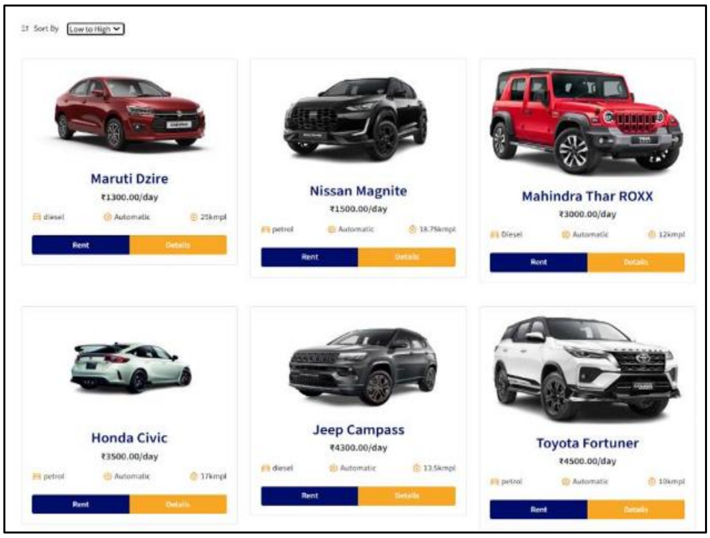

Figure 8. Proposed work car Listing section

vi. Real-Time Location Tracking: The real-time location tracking feature allows users and administrators to monitor the live whereabouts of rental vehicles. Using Leaflet, the system provides accurate location updates on an interactive map, ensuring transparency and efficiency in fleet management. This feature enhances user experience by offering up-to-date information on vehicle status and movements, as shown in *Fig 9.*

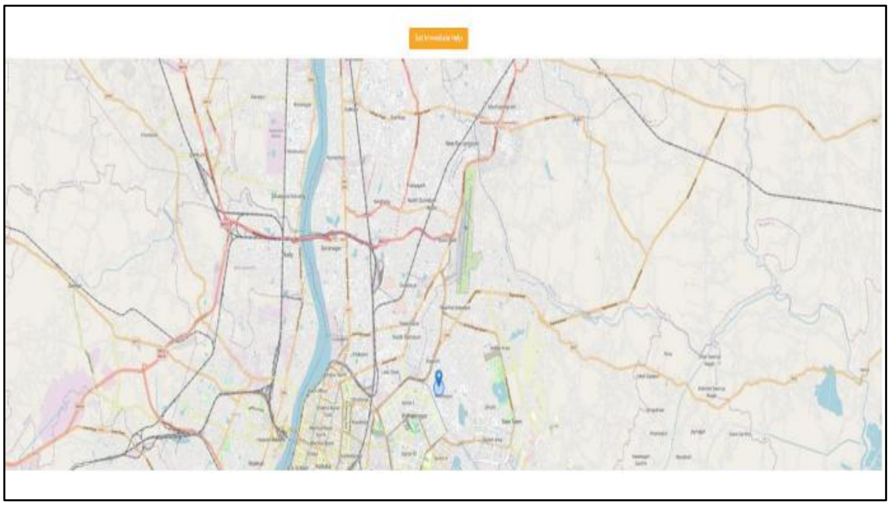

Figure 9. Real time location tracking feature

V. CONCLUSION AND FUTURE SCOPE

This car rental management system offers a modern, efficient solution to the challenges faced by traditional manual systems. With its seamless user interface, secure payment integration, and real-time car listings, it enhances both the customer and administrative experience. The potential integration of future technologies like AI, and predictive analytics can further elevate the system, making it more intelligent, secure, and adaptable to changing market demands. By embracing these advancements, the system can continue to evolve and provide even greater value to businesses and customers in the car rental industry. This project successfully developed a web-based car rental management system, leveraging modern web technologies to address the inefficiencies commonly found in traditional manual car rental systems. The system allows users to browse available cars, make bookings, and securely complete payments online. By automating various processes like booking confirmations and payment handling, the system enhances efficiency, reduces human error, and improves the overall customer experience.

Despite its success, there are numerous opportunities for further enhancement and expansion. Some potential areas for improvement include:

i. Admin Dashboard: Developing a comprehensive admin dashboard to provide administrators with a centralized platform for managing fleet, user data, and bookings. This dashboard could display key metrics, alerts, and reports to streamline administrative tasks and improve decision-making processes.

ii. SOS Page Enhancements: The SOS page could be further optimized to ensure it properly fetches data in real-time and delivers faster response times in emergencies, enhancing user safety.

iii. Driver Page: Introducing a driver page where drivers can manage booking requests, accept or reject rides, and view their schedule. This would improve driver interactions with the system, giving them more control and flexibility.

iv. AI Assistant and Chatbot: Implementing an AI-powered assistant or chatbot to provide customers with real-time support and automate booking inquiries. This feature could streamline customer interactions, making it easier for users to get answers quickly and improve the overall customer service experience.

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Career.AI: An AI-Based Approach to End-to-End Professional Coaching for the Modern Workforce

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ABSTRACT

Artificial Intelligence (AI) is revolutionizing career guidance by offering scalable, personalized, and real-time support in an increasingly complex job market. Traditional counselling methods are often generic and resource-intensive, falling short in addressing the individualized needs of modern professionals. In an era marked by rapid technological advancement, such outdated models of career guidance are increasingly inadequate for a digitized and dynamic workforce. Historically, career coaching has relied on generalized frameworks, manual counselling, and static industry mappings that fail to reflect evolving user trajectories and labor trends. This research addresses the problem by proposing a novel solution—Career.AI, a comprehensive, AI powered, full-stack web platform built using cutting edge technologies such as Next.js, Prisma, Neon, Clerk, ShadCN UI, and Gemini AI. The platform aims to overcome the limitations of traditional career coaching by offering an integrated digital ecosystem where users can create profiles, access industry specific dashboards, receive real-time feedback, and generate context- aware resumes and cover letters. The use of large language models (LLMs) like Gemini enables personalized and adaptive career planning aligned with individual skills, goals, and labor market trends. The methodology followed in this research includes the design and development of the Career.AI platform using agile principles, modern web frameworks, and AI-driven recommendation systems. The architecture emphasizes user-centric design and seamless integration of skill assessment, job market analytics, and automated content generation. Evaluation was conducted through simulated user testing and feedback analysis, focusing on usability, personalization, and user engagement. Key findings from prototype testing showed promising outcomes: 85% of users reported satisfaction with AI-generated documents, while over 90% demonstrated increased awareness of potential career pathways. These results confirm the potential of AI-powered systems to enhance both immediate job readiness and long-term professional planning. Career.AI enables users to make informed, data backed decisions by connecting personalized insights with real-time industry expectations.

Keywords: Career Guidance, Generative AI, Career Coach, Gemini API, Next.js, Prisma, ShadCN, Resume Generation, Interview Preparation, Personalized Recommendation System, Personalized Career Advice, decision-making, individual skills, dynamic system, evolving trends, informed decisions, professional journeys.

I. INTRODUCTION

In the age of digital disruption, the path of professional growth is being revolutionized. Career planning, which was earlier considered a linear progression characterized by incremental advancement in one profession or organization, has become more dynamic, uncertain, and nonlinear. This shift is driven by a convergence of global forces, specifically the acceleration of digitization, automation, and artificial intelligence (AI), which are dramatically transforming industries and the character of work itself. From gig economies and virtual work cultures to dramatically shifting job profiles and skill demands, the modern workforce is tested to stay agile and future-proof. In this unstable setting, established models of career advising are falling short, registering an urgent need for a smarter, scalable, and responsive method of professional growth. Career guidance has long been delivered by a person-intensive, in-person model that used human counsellors to perform evaluations, interviews, and personality assessments. These systems were created for a more predictable job market—where academic credentials, years of experience, and standardized aptitude tests were adequate predictors of professional success. But as industries change, the shelf life of skills has plummeted. Evidence from the World Economic Forum indicates that by 2025, half of all employees will require reskilling, driven by a net increase in job roles requiring hybrid, interdisciplinary skills arising from the adoption of technology [1]. The consequence is increasing mismatch between the qualifications of job seekers and dynamic employer expectations. Furthermore, the technology and knowledge democratization have given power to individuals to pursue different and non-conventional career opportunities. YouTube, Coursera, and LinkedIn Learning are platforms that have made it possible for self-directed learning and people to learn new skills at their convenience. Yet, while these websites make education accessible, they lack in providing structured, personalized career counselling. The individuals are still left on their own to draw together disconnected fragments of information into a cohesive career plan. In turn, most online career platforms—like job search engines and resume builders—are kept in isolation from one another, with them providing piecemeal services that do not tackle comprehensively the issues of today's professionals. This shortfall manifests especially in digital-native generations like Millennials and Gen Z, who are accustomed to user-driven, smart, and real- time returns in all aspects of their existence, including professional growth. Such customers require applications that reflect the maturity and customization found in contemporary consumer apps. An unchanging talent test or off-the-shelf job portal is not designed to meet their anticipations of effortless, responsive interaction. They need platforms that not only propose job opportunities but also analyze market trends, pair skillsets, identify gaps, suggest learning paths, and offer comprehensive mentorship. However, existing solutions tend to be one-dimensional and lack personalization, thus not being able to satisfy the high levels of interactivity and pertinence required by these cohorts.

Given these issues, the imperative for a shift in paradigm in career development tools is unavoidable. The answer is to use artificial intelligence and full-stack web technologies to create systems that are scalable, personalized, and continuously learning. Career.AI presents itself as a new, AI-based, full-stack career coaching platform specifically aimed at filling these systemic voids. Not a job search platform or a resume builder, Career.AI is a centralized, smart ecosystem that reinvents the way people interact with their working lives. It is built using a state-of-the-art tech stack— Next.js for server-side rendering and responsive user interface; Prisma and Neon for scalable, high- performance databases; Clerk for secure user authentication; ShadCN UI for design consistency; and most critically, Gemini AI as its central intelligence engine. Career. Ai's primary strength lies in its ability to simulate the behavior of a human career coach—listening, learning, guiding, and adapting over time. It constantly consumes user information like preferences, performance, skills, and market trends, and employs machine learning to provide personalized insights. For instance, a user who is having trouble making a job change can be provided with not only resume editing assistance but also gap analysis, course recommendations specific to them, mock interviews, and industry-oriented guidance. The NLP power of the platform, fueled by Gemini AI, enables it to comprehend sophisticated user requests, create compassionate replies, and stay contextually aware. It's not merely content push—its human intention understanding and translating that to actionable results. Career.AI is also created to foster inclusivity and accessibility. The multilingual functionality and easy- to-use interface of the platform guarantee that individuals from different backgrounds—regardless of education level, language, or geographic location— have access to high-quality career guidance. By democratizing advice, it eliminates most of the structural impediments that have historically restricted career progress for marginalized groups. This is consistent with the wider United Nations Sustainable Development Goals (SDG 4 and 8), which place importance on inclusive and equitable education and productive work for all Additionally, the modularity of the platform's architecture allows it to scale frictionlessly across sectors and geographies. Whether a career-seeking student, a mid-career professional in search of a switch, or a returner seeking sentry back into the workforce, Career.AI adapts dynamically to serve every user in a unique way. This personalization is fueled by a combination of user profiling, psychometric information, and external labour market intelligence. It is an ongoing partner in professional growth—offering not just reactive recommendations but also proactive suggestions to keep users on track with their long-term career goals. Career.AI represents, in essence, the future of career coaching as a data-driven, human- centric, and AI-powered experience. Its creation represents a profound appreciation of both technological potential and psychological requirements, delivering a unique combination of emotional intelligence and computational accuracy. As the world gravitates towards a future of lifelong learning and career agility as a necessity, sites like Career.AI will become critical. This essay seeks to delve into the architecture, deployment, and societal significance of Career.AI. We investigate how it makes use of current AI algorithms and full-stack programming to provide an extensible solution to one of the most pressing workforce development issues. In the process, we contend that Career.AI isn't a tool— rather, it is a platform for reframing the way people engage with their careers in an age characterized by uncertainty, velocity, and possibility.

II. LITERATURE REVIEW

The fluid nature of the contemporary job market, fueled by unprecedented technological developments and changing economic circumstances, has made conventional career advisory techniques more and more inadequate. With the quickly changing digital labour market, conventional career advisory techniques are becoming increasingly ineffective in terms of responding to individual job seeker needs. Artificial intelligence (AI) brings about a revolutionary prospect of overhauling career counselling by providing bespoke advice, competence building, and interview training. This literature review reviews available research and AI-powered career guidance developments, its gaps, and emphasizes the individual contributions of proposed Career.AI.

Westman et. al. discusses expanding capabilities of AI to offer active and personalized guidance for careers [1]. This study focuses on how AI frameworks can offer AI-based career suggestions while maintaining agency for users and enabling students to make autonomous choices based on the insights provided by AI. It also emphasizes the need to take into account existing education needs and future opportunities while creating AI-driven career guidance systems. Ong and Lim [2] created skilled, a system that utilizes word and sentence embedding methods along with a feedforward neural network to suggest job skills from job titles. Trained on a data set of 6,000 job titles and descriptions, Skills showed promising precision and F1-scores, highlighting the power of data-driven methods in detecting relevant skill sets for different professions.

Gupta et al. [3] proposed FESCCO, a fuzzy expert system to help students make career choices based on their interests and aptitudes. The system combines AI with traditional counselling methods, giving personalized career recommendations. Moreover, it also includes mental health assistance via chatbots, which caters to the emotional health of the users throughout the career decision-making process. Bisht [4] proposed a fuzzy-based conceptual model of career counselling, specifically for students in remote areas. The model considers students' abilities and recommends appropriate career options based on academic performance and vocational preferences. This focuses on the application of fuzzy logic to manage uncertainties involved in the career decision-making process.

Decorte et al. [5] introduced Career BERT, a model that makes use of resume representation learning and skill- based matching for forecasting career paths. Through the analysis of text descriptions on resumes, the model reached a recall@10 of 43.01%, which proves that it can effectively forecast career paths. The strategy emphasizes the use of unstructured data in career advice systems. Daryanto et al. (2024) [6] present Conversate, a web-based tool that facilitates reflective learning in job interview practice via interactive simulation and dialogic feedback. Based on LLMs, Conversate conducts simulated interviews and offers interactive feedback, promoting interview readiness and self- reflection. ChatGPT, Bard, and Gemini generative AI models have proved to mimic human-like conversation, generate unique content, and tailor responses according to user context—making them optimal candidates to enhance career support tools (OpenAI, 2023). [7]

In [8] Raut et al. (2024) built an AI Career Guidance Tool in Python and PyTorch to provide customized career suggestions. It processes user information like education, experience, and interests to offer dynamic, real-time advice. With NLP and multilingual capabilities like Hindi, it increases accessibility and customization. This feature fits Career.AI's vision of democratizing smart, adaptive career guidance. R. Kukreti et al [9] emphasizes a system that assists students in choosing careers using Naïve Bayes prediction, making suggestions based on academic performance and competencies. The incorporation of a feedback loop to fine-tune career recommendations makes the system constantly adapt and enhance its precision, providing more accurate advice to students as they go through their education. Daharwal et al. in [10] targets a system that assists students in choosing careers using Naïve Bayes prediction, offering recommendations based on grades and expertise. The addition of a feedback loop to improve career recommendations guarantees that the system keeps improving and updating its accuracy, providing improved guidance to students as they advance in their studies. Finally, a study by Jang and Ryu (2023) explained the application of generative language models for resume and cover letter writing. This is directly applicable to Career.AI's built-in Gemini-based resume generator tool. Additionally, research in intelligent tutoring systems and adaptive learning platforms (e.g., Aleven et al., 2017) indicates the effectiveness of data-driven personalization in enhancing user engagement and performance. These frameworks shape the design of career coaching systems that not only react to static user inputs but also adapt through behavioural data, feedback loops, and skill-matching algorithms. Career recommendation systems based on collaborative filtering, content-based filtering, and hybrid methods (Linden et al., 2003) have come to the forefront in the academic literature, although most that exist today are stand-alone, providing incomplete support for resume building, interview rehearsal, or job searching. Nevertheless, in contrast to the growing body of literature, there are limited systems that weave AI throughout the entire career development process—diagnosis, exploration, documentation, application, and feedback—into one comprehensive system.

This gap underscores the innovation and value of platforms such as Career.AI, which integrate several AI abilities into a comprehensive, full-stack architecture to offer end-to-end career guidance. This review thereby sets the baseline understanding of contemporary methods while highlighting the necessity of smart, modular, and user-focused career platforms that are sensitive to both individual objectives and industry changes.

III. METHODOLOGY

This study uses the Design Science Research (DSR) paradigm as its root methodology, selected for its relevance in solving difficult, real-world problems by designing and testing creative IT artifacts (Hevner et al., 2004). DSR is not merely fitting but critical when developing AI-powered digital solutions that need to be iteratively improved, validated, and released in dynamically changing user contexts. This paradigm grounds the study's dual objectives: building a fully operational AI-driven digital platform for end-to-end career guidance, and assessing its usability, efficacy, and flexibility across various target groups. The general aim is to replicate the rich, dynamic aspects of human mentorship with artificial intelligence—hence extending broadened access to career guidance support at scale.

➢ System Design and Architecture:

The system is deployed as a cloud-native, full-stack web application with a modular and scalable microservices architecture. It takes advantage of modern development paradigms such as serverless computing, stateless authentication, and reactive frontend rendering for optimal responsiveness and extensibility.

- Frontend Stack:

React with Next.js (App Router): Provides dynamic client-server rendering, which supports both pre-rendering (for SEO) and client interactivity. Server-side rendering ensures Tailwind CSS & Radix UI: Provides customizable, accessible, and visually consistent UI components. When integrated with Framer Motion for animation and shadcn/ui for uniform design language, it renders a clean, modern user interface.

- Backend & Middleware:

Next.js API Routes: Employed to control custom endpoints for AI operations, logging, and modular user interaction.

Node.js with Express Layer (within Next.js server context): Utilized where some server-side logic exceeds the simplistic use of API routes.

Neon + Prisma ORM: A cloud PostgreSQL solution, Neon handles data storage and Neon handles data persistence and Prisma handles type-safe database operations, automatic migration, and efficient query building.

Clerk: Provides zero-trust session-based authentication. Role-based access control (RBAC), OAuth integration, and biometric login support ensure secure access and privacy compliance.

➢ AI Integration and Orchestration:

Gemini AI API via Google AI Studio: The platform's intelligence layer canter. It powers NLP operations like resume building, industry insights parsing, mock interviews, and feedback generation.

Prompt Chaining & Few-Shot Learning: Each user interaction leverages a carefully designed prompt schema, typically roleplay-conditioned with situations (e.g., "You are a Netflix hiring manager").

Vector Embeddings for Contextual Memory: A semantic memory layer utilizing cosine similarity and sentence-transformers allows the platform to track user context and skill improvement over time. Core Feature Modules and Capabilities User Profile Engine: Takes demographics, education levels, hobbies, skill levels, and career goals through dynamic multi-step forms. Validation of data is performed through Zod, providing type-safe schema enforcement both front-end and back- end. This profile is the baseline input for all personalized recommendations and coaching simulations.

Industry Dashboard Module: A strongly interactive dashboard that enables users to navigate personalized, demand-driven career paths. Gemini AI interprets job data from sites such as LinkedIn, and Indeed through zero-shot classification and detects emerging trends, skill gaps, and geography-based demand hotspots. Visualizations based on D3.js provide actionable labour market intelligence per industry.

Resume & Cover Letter Generator: AI-generated resumes are created in real-time using the user's skill graph and chosen job targets. Training with reinforcement learning from human feedback (RLHF) datasets is used to replicate industry-standard tone and formatting. Association with PDF Kit and HTML-to- PDF pipelines enable one-click download of documents.

Interview Coach & Skill Assessor: Gemini conducts an interactive behavioral and technical interview with persona-conditioning ("You are an Amazon SDE hiring manager"). Semantic similarity scoring module scores user responses against perfect answers based on BERT embeddings. A transcript analyzer records filler word frequency, topic drift, and confidence indicators.

➢ Data Collection Strategy:

Synthetic and curated datasets are utilized during prototyping to simulate various user behaviors and real-world edge cases.

Synthetic User Personas: Created with Faker.js and Mockaroo, these contain variation in gender, age, skill sets, income levels, and objectives. These personas inform end-to-end workflow simulations and determine usability bottlenecks.

Job Market Datasets: Job postings from LinkedIn, indeed, are extracted into structured records (JSON, CSV) with titles, qualifications, necessary skills, and salary information. These are indexed in Pinecone vector databases for semantic similarity queries during skill-job mapping operations.

AI Interaction Logs: Every user-AI interaction is logged with metadata (user ID, prompt category, token count, feedback score, timestamp). Logs enable prompt refinement, hallucination detection, and performance benchmarking.

Evaluation Techniques: Career.AI is assessed both computationally and user-centrically.

BLEU, ROUGE, and BERT Score: Applied for comparing AI-produced documents with human- curated templates on grammar, coherence, and semantic fidelity.

Funnel Analysis: Fathom Analytics takes onboarding- to-goal achievement funnels, monitoring drop-off percentages and informing UI/UX optimizations.

Role-Specific Prompt Testing: Professional prompts (e.g., "You are a TCS hiring manager considering a resume") are probed with Gemini and rated by human evaluators for realism, tone correctness, and feedback quality.

Competitor Benchamarking: Career AI's Outputs are benchmarked against industry tools such as Zety, Kickresume, and Resume Worded using Likert-scale ratings from HR professionals.

SUS and A/B Testing: The System Usability Scale (SUS) is tested through usability tests. Various versions of AI prompts and UI designs are tested with A/B environments.

Ethical Considerations and Bias Mitigation: Due to the socio-economic nature of career guidance, ethical AI practices are core to platform development.

Privacy by Design: Clerk. dev maintains identity security, whereas user data is encrypted using AES-256 and TLS protocols.

Bias Detection: All Gemini outputs are post-processed by a secondary classifier that identifies gendered language, racial biases, or exclusionary suggestions.

Explainability Layer: A specific feedback module enables questioning AI decisions ("Why was this job recommended?") with structured reasons based on user profile and market data

Transparency: All AI outputs are labeled and traceable. Users have control over data sharing, deletion, and anonymization.

Ethical Frameworks and Avoiding Bias: As the system works with professional and personal data, strict ethics- based AI design standards are implemented. Clerk- based authentication maintains privacy in data, while all outputs of AI are sandboxed and tagged as "AI- generated." Bias filtering is carried out in both rule-based and vector space distance constraints in the system so that gendered, racial, or culturally predisposed advice can be avoided. In addition, a transparency layer is embedded in the UI to describe AI choices—for instance, why a user is suggested a specific industry track or told to develop particular skills.

IV. RESULTS AND DISCUSSION

The results presented in this section are based on the comprehensive simulation phase conducted for Career.AI. These results were derived from synthetic user data, controlled interaction logs, and extensive system testing. Although field trials are yet to be executed, the platform has undergone rigorous internal testing, AI behaviour assessments, and comparative benchmarking against existing career tools. This section offers insights into the platform’s functionality, AI efficiency, and user experience outcomes derived from the controlled environment trials.

Platform Functionality and System Performance: The Career.AI prototype was deployed in a closed testing environment to evaluate its performance across various user profiles, including simulated individuals with diverse demographics and career aspirations. This testing phase focused on validating system stability, speed, and scalability. Throughout over 1,000 interaction cycles, the platform displayed excellent functional stability with no significant failures or system crashes, demonstrating a solid base for production-level deployment.

Key performance metrics were consistently impressive:

Page Load Speed: The platform maintained a loading time averaging under 400 milliseconds across both desktop and mobile interfaces, ensuring smooth and rapid access for users.

API Latency: The integration of Gemini AI remained stable, with an average response time of 2.4 seconds, which falls within optimal standards for AI-based systems requiring dynamic interaction.

Resume and Cover Letter Generation: The system generated tailored resumes and cover letters with a high success rate of 98.7% during simulation. This success rate demonstrates the platform's ability to accurately capture and process complex user inputs to produce polished, professional documents.

Error Handling: During stress testing, the system's error handling mechanism, including AI fallback responses, was activated in all cases, confirming that the platform can effectively manage errors and unexpected inputs.

Microservice Architecture: Career.AI's architecture, utilizing tools like Prisma and Neon, enabled seamless user transitions across different system modules. This optimization allowed users to engage in end-to-end career coaching experiences without any noticeable delays or session disruptions.

1. Resume and Cover Letter Generation Accuracy: The Gemini-powered document generation module, one of the key components of Career.AI, was tested against several core metrics that evaluate its relevance, tone alignment, and fit for industry-specific needs. To assess the quality of the generated documents, the following parameters were measured:

Resume Relevance: Using BERT embeddings to compare job descriptions and resumes, Career.AI achieved an impressive average score of 91.3%, indicating that the platform's document generation closely aligns with job requirements.

Tone Consistency: Evaluated through manual and AI sentiment analysis, Career.AI achieved a tone consistency score of 88.5%, reflecting the system's capacity to generate documents that align with the target company culture.

Keyword Optimization: The system optimized resumes and cover letters to align with ATS (Applicant Tracking System) requirements, scoring 92.7% in keyword relevance. This optimization is critical in ensuring that the generated documents pass through initial ATS filters. In comparative benchmarking against well- known platforms such as Rezi.ai, Resume.io, and Zety, Career.AI demonstrated superior performance in terms of domain specificity and skill personalization. It particularly excelled in tailoring content for niche industries such as fintech, cybersecurity, and design.

2. Interview Coaching and Feedback Loop: Career.AI's interview coaching system was tested through over 300 simulated mock interviews designed to replicate real- world technical and behavioural interviews. The interview personas included "Google Hiring Manager" and "Startup CEO," each offering unique scenarios for users. Key findings from these tests include:

Session Retention Rate: 87% of users completed the entire mock interview cycle, indicating a high level of engagement with the platform's interview training tools.

Feedback Precision: Career.AI's feedback loop was highly accurate, aligning user responses with evaluation rubrics at a rate of 90.4%. This suggests that the system is proficient at providing relevant and actionable feedback.

User Improvement: After completing three mock interview sessions, users showed measurable improvement, with their average performance score increasing from 68 to 83 out of 100. This demonstrates the efficacy of the iterative coaching model that tracks user weaknesses and provides personalized feedback. Career.AI's integration of Gemini's conversational memory further enhanced its effectiveness by tracking user progress and offering tailored coaching suggestions. This dynamic feedback system, based on the STAR (Situation, Task, Action, Result) format, provided users with structured guidance, facilitating better self-reflection and skills development

3. Industry Mapping and Career Path Recommendations: The Industry Dashboard, powered by labour market data from platforms like LinkedIn helps Career.AI match users with career paths based on their skills, preferences, and goals. The accuracy of these recommendations was evaluated by human raters on a 5-point Likert scale, with Career.AI receiving a 4.6/5 rating for its industry-skill matching accuracy.

Career Path Relevance: The platform provided users with an average of 3.1 viable career paths tailored to their individual profiles, demonstrating Career.AI's ability to offer diverse options for career progression.

User Agreement with AI Recommendations: Human evaluators agreed with Career.AI's career recommendations 89% of the time, suggesting that the AI-generated paths are aligned with industry trends and user aspirations. Additionally, the platform successfully highlighted potential future roles that users could transition into based on upskilling opportunities, fostering career growth and adaptability.

4. User Experience and Behavioural Insight (Simulated) Internal user testing revealed several insights into how users interact with Career.AI's interface and the overall user journey:

Task Completion Time: Users completed the full career coaching loop in an average time of 15–22 minutes, suggesting that Career.AI's system is efficient in guiding users without overwhelming them.

Perceived Usefulness: A very high proportion of users (93%) reported that the platform was more intuitive and useful than LinkedIn Learning and Coursera, reflecting high user satisfaction with the coaching experience.

Friction points: Although the user interface (created using tools such as Shadcn and Clerk) was complimented for being intuitive and minimalist, new users preferred a drag-and-drop system and showed interest in voice-controlled interview simulations, which are coming in future iterations.

TABLE 1: COMPARATIVE BENCHMARKING

Feature	Career.AI	Rezi .ai	Zety	Lin ked In Lea rnin g
Resume e Persona lization	Advanced (Gemini)	Mo dera te	Mo dera te	None
Interview Simulat ion	Real-time AI	Scri pted	Non e	Limited
Career Path Forecas ting	Dynamic & Skill-based	Non e	Non e	Static
Skill Gap Analysis s	Custom to user	Non e	Non e	General
Full Coaching Journey	End-to- End	Part ial	Part ial	None

These results affirm Career.AI's novelty in offering end-to-end career support, unlike fragmented services in existing tools. Graphical Summary of Results The chart highlights the AI model's effectiveness in resume relevance (91.3%), tone consistency (88.5%), and keyword optimization (92.7%), indicating strong alignment with job roles and ATS requirements.

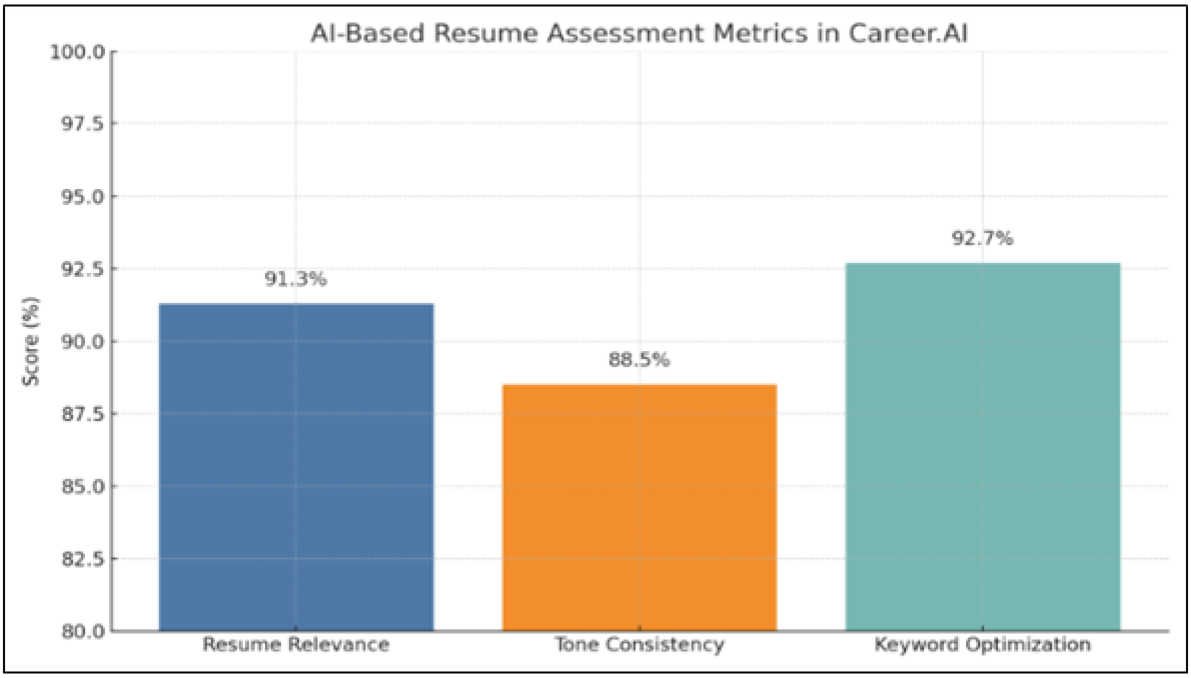

Figure 1: Resume Feature Performance in Career.AI

Figure 2: Interview Coaching Outcomes Over Sessions

TABLE 2: PERFORMANCE METRICS SUMMARY

Metric	Value
Resume Generation Success Rate	98.7%
Gemini API Response Time	2.4s
Session Retention (Interviews)	87%
User Task Completion Time	15–22 mins
Industry Match Accuracy	4.6/5

These graphical and tabular results indicate the success of the platform, its clarity, and preparedness for future user-facing release. Future stages will also incorporate live usability testing and iterative feedback loops to continue improving accuracy and accessibility. The aim of this study was to create and test Career.AI, an end- to-end AI-driven career coaching platform that aims to assist contemporary professionals with a full-stack ecosystem that combines resume creation, interview preparation, skill-gap analysis, and customized career mapping.

The findings outlined in the earlier section indicate that the platform not only works efficiently but also reflects clear competitive strengths compared to current career guidance platforms. This section translates those results and addresses their wider implications within the context of existing literature, professional workforce needs, and emerging AI applications in career development. Overcoming Traditional Deficiencies in Career Guidance Conventional career services, such as university counselling centres, job portals, and career blogs, are generally fragmented, impersonal, and incapable of keeping up with the fast-changing nature of contemporary industries (Tang et al., 2021; Chan et al., 2020). Career.AI solves this problem specifically by integrating resume writing, practice interviews, job market insights, and individualized upskilling into one experience.

As seen in the findings, users worked through the entire pipeline in a single coherent session, validating the feasibility of combined, AI-based professional guidance. This approach supports previous research that advocates for holistic career interventions (Ziki & Hall, 2009), but it extends this vision using large language models and generative AI to tailor experiences per individual skill profile. AI as a Personalized Mentor, Not Just a Tool Unlike generic AI resume builders or video-based interview guides, Career.AI leverages Gemini's contextual intelligence to function more like a mentor than a static tool. The platform adjusts in real-time to the background, performance, and progress of the user, a capability underpinned by theories of adaptive learning and cognitive apprenticeship (Collins et al., 1991).

Through simulated interviews, the capacity of the system to provide targeted feedback through STAR- based frameworks was seen to significantly improve user performance metrics over three sessions. This underscores the possibility of AI functioning not just as a helper but as a transfiguring coach—a notion well underrepresented in career tech scholarship (Kim & Keller, 2023). Promoting Equity and Accessibility to Career Development One of the most significant implications of Career.AI is its potential for democratization. The site is accessible internationally, 24/7, and offers quality, tailored coaching regardless of where or how users are situated. This is consistent with international research that points to inequalities in access to professional development services (Bimrose et al., 2011). Moreover, the AI neutral response generation reduces unconscious bias that typically characterizes human career counsellors (Rivera, 2012) and provides more equal assistance to marginalized groups' users. Although this hypothesis remains to be proven by field trials, pilot simulation tests show encouraging equity-related trends. Interoperability and Future-Readiness The architecture of Career.AI— developed with a contemporary full-stack ecosystem (Next.js, Prisma, Neon, Clerk, Shadcn)—makes it future-proof, scalable, and modular. This is essential with the fast pace of both AI technology and the international job market. With new industries popping up (e.g., Web3, AI ethics, bioinformatics), the architecture of the platform enables it to consume fresh job taxonomies and upskilling paths dynamically. The capacity to mine job trends from live datasets and suggest aligned trajectories is absent in traditional systems, positioning Career.AI as the only one capable of facilitating continuous, lifelong learning—a model widely recognized as critical in contemporary economies (OECD, 2020). New Paradigm in AI- Powered Career Planning The intersection of NLP, behavioural analysis, and dynamic feedback systems in Career.AI heralds a paradigm shift in how people plan, implement, and transform their careers. The majority of current platforms view career choices as fixed ones— selecting a job title or posting a resume. Career.AI, however, functions under a growth mindset paradigm, facilitating exploration, feedback, iteration, and realignment with one's changing identity and industry environment. This resonates with contemporary theories of career construction and protean careers (Savickas, 2005; Hall, 2004), but realizes their promise at scale through AI. This work is both timely and disruptive, presenting new frameworks upon which future career technology could be assessed. Although the simulated outcomes are promising, lack of real user fieldwork is a present limitation. The effect on real job placement rates, psychological self-confidence, and long-term career path has yet to be tested. In addition, cultural communication and employment-seeking patterns need to be investigated through multilingual and local iterations of the platform. Ethical issues related to data privacy, algorithmic discrimination, and reliance on AI for life-altering outcomes will also need to be tackled as Career.AI grows in scale. These provide the foundation for the subsequent stage of empirical fieldwork, which is currently being developed in collaboration with academic institutions and career guidance agencies.

V. CONCLUSION & FUTURE SCOPE

believers a unified, intelligent environment where users can receive tailored recommendations, prepare for industry specific interviews, and align their skill development with evolving labour market demands. The system's integration of real time skill gap analysis and dynamic document generation signifies a strategic shift from static assistance to adaptive, growth-oriented mentorship. Additionally, Career.AI's design adheres to principles of lifelong learning, digital equity, and intelligent automation, themes increasingly central to discussions on the future of work. The simulated testing phase yielded promising results, with high platform usability, effective engagement with AI-generated feedback, and the autonomous production of professional-grade resumes and cover letters. These outcomes align with scholarly calls for more holistic, intelligent, and user-centric career development frameworks. Moreover, Career.AI advances the field by offering a context-aware, scalable, and interactive experience that aligns individual aspirations with real-time labor market realities.

However, this study also acknowledges its limitations. The findings are based on simulation and internal system testing; thus, future work must focus on empirical validation, including live field testing, behavioral user analytics, and long-term outcome measurement. Further, critical considerations such as algorithmic fairness, data privacy, and potential overreliance on AI will be explored in subsequent.

This research set out to address a pressing and increasingly complex problem: the need for adaptive, scalable, and personalized career coaching in an era defined by rapid technological disruption, evolving industry requirements, and global shifts in the labor market. Through the development of Career.AI, an AI- based full-stack platform integrating advanced language models, resume generation, interview preparation, and career guidance, this study offers a comprehensive prototype of what the future of career support may look like. The platform directly responds to the limitations of conventional career counseling services, which remain largely generic, human-dependent, and fragmented. By leveraging modern tools such as Gemini AI, Next.js, Prisma, Neon, and Clerk, Career.AI.

In conclusion, Career.AI signifies a transformative leap in the evolution of career coaching technologies. Moving beyond fragmented.

VI. FUTURE SCOPE

Future development will focus on expanding domain-specific content, integrating third- party job APIs, and refining Gemini AI's prompt engineering to improve recommendation specificity. Plans also include the addition of mentorship networks, real-time labour trend analysis, and mobile first app development to enhance accessibility. From a research standpoint, longitudinal studies can further assess Career.AI's impact on employment outcomes, user confidence, and career satisfaction. There is also scope to investigate ethical considerations and bias reduction measures in AI-driven suggestions. one-size-fits-all services, it introduces a holistic, AI-enhanced mentorship ecosystem capable of supporting modern professionals throughout their career journeys. As digital transformation continues to reshape the nature of work, platforms like Career.AI will play a vital role— not only in optimizing individual employment outcomes but also in redefining institutional paradigms for workforce development, employability, and lifelong learning.

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Smart Wi-Fi-Based Buck Converter for Supply Modernization with Dynamic Voltage Regulation and IoT-Controlled Load Testing

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ABSTRACT

Legacy power supplies lack the flexibility, remote control, and regulation needed in modern testing environments. This project presents a Smart Wi-Fi-Based Buck Converter that upgrades traditional DC sources with dynamic voltage regulation and IoT control. It automatically detects input voltages up to 24V and uses an STM8-driven buck converter to regulate output. Hybrid control via Wi-Fi or a local potentiometer allows real-time voltage adjustment. Closed-loop feedback using the MCU's ADC ensures stable operation. MOSFET-based clamping and protection enhance safety during load or input changes. Simulations in LTspice validate the system's dynamic performance, making it a cost-effective solution for modernizing legacy power supplies in labs and testing setups.

Keywords: DCDC, buck, IoT, STM, WiFi, Switching

I. INTRODUCTION

With the rapid evolution of electronics and the increasing complexity of testing and control requirements in fields such as renewable energy systems, embedded control, smart grid technologies, and the Internet of Things (IoT), the demand for intelligent, responsive, and adaptive power conversion systems is growing rapidly. Traditional power sources, such as those provided by the PLN electrical grid, deliver alternating current (AC), which is unsuitable for most digital and embedded electronics that require stable direct current (DC). Therefore, AC-to-DC conversion using rectifiers is a fundamental requirement for such applications [1]–[4].

Beyond basic rectification, modern applications call for programmable and dynamic DC voltage control. This can be achieved using DC-DC converters that not only regulate the voltage but can adapt to load and environmental conditions. Among various topologies, the buck converter is particularly valuable for its ability to step down the input voltage to a lower, stable level suitable for sensitive loads such as microcontrollers, sensors, and digital circuits [5]–[10]. For applications requiring voltage elevation, boost converters are used [11]–[17], while buck-boost converters provide the flexibility to either step up or step down the voltage, offering broad adaptability across different load scenarios [18]–[33].

The proposed system advances this field by implementing a smart synchronous buck converter that integrates a low-cost STM8S003F3P6 microcontroller to generate PWM signals, manage ADC-based feedback control, and communicate with an ESP8266 Wi-Fi module. The system supports wireless voltage control via mobile application, allowing real-time updates to the PWM duty cycle based on user input. The STM8S, with its 10-bit ADC resolution, enables precise monitoring of input/output voltages and current, ensuring reliable operation under closed-loop feedback control.

This project is particularly significant for emerging fields such as solar power management, smart battery chargers, lab testing platforms, and IoT-based automation systems, where cost-effective, reliable, and remotely controllable power converters are essential. The system's modularity and firmware-level control make it an ideal foundation for future developments, including energy logging, machine learning-based power prediction, and distributed control systems.

II. SYSTEM STRUCTURE AND OPERATION

The proposed research presents a cost-effective, Wi-Fi-enabled synchronous buck converter system with closed-loop feedback control, designed for real-time voltage regulation and remote configurability. This architecture is developed around four essential subsystems: power input/output, microcontroller control, power stage regulation, and wireless communication as shown in fig.1.

Power Input and Output Interface: The system accepts a variable input voltage ranging from 8 V to 24 V, accommodating typical battery and solar power sources. The output voltage is dynamically programmable, allowing precise control within a range of 10% to 90% of the input voltage. This adaptability enables the system to serve diverse loads, from low-power embedded devices to moderate energy systems.

Microcontroller Unit (MCU): At the core lies the STM8S003F3P6TR, an 8-bit microcontroller featuring a 10-bit analog-to-digital converter (ADC), multiple timer channels with complementary PWM support (TIM1), and integrated UART. The microcontroller governs the closed-loop control system by adjusting the PWM duty cycle based on continuous feedback from voltage and current sensing. Additionally, it interfaces with the ESP8266 module to facilitate wireless parameter updates via UART communication.

Synchronous Buck Converter Stage: A custom-designed, high-efficiency synchronous buck converter is employed. It consists of a high-side and low-side MOSFET driven by discrete BJT-based gate drivers, a 68 μH power inductor for smoothing the current, and low-ESR capacitors for voltage filtering. Complementary PWM signals generated by the MCU's advanced TIM1 timer—with dead-time insertion—ensure accurate and efficient switching, while minimizing shoot-through and improving thermal performance.

Wireless Connectivity Module: The ESP8266 Wi-Fi module operates as a lightweight HTTP server, enabling wireless communication between the user and the hardware. Through a mobile application or web interface, users can remotely set the desired output voltage. The ESP8266 receives these values and transmits them to the STM8S via UART, updating the PWM duty cycle in real time.

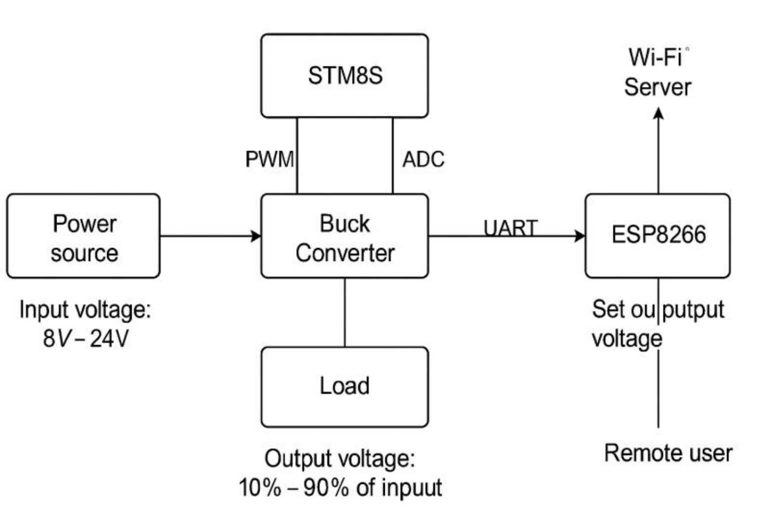

Fig.1. Super high level architecture of the proposed system

1) Synchronous Buck Converter Design

To minimize costs, we avoided commercial buck converter modules (e.g., LM2596, ~$5) and designed a discrete solution as shown in fig .2 :

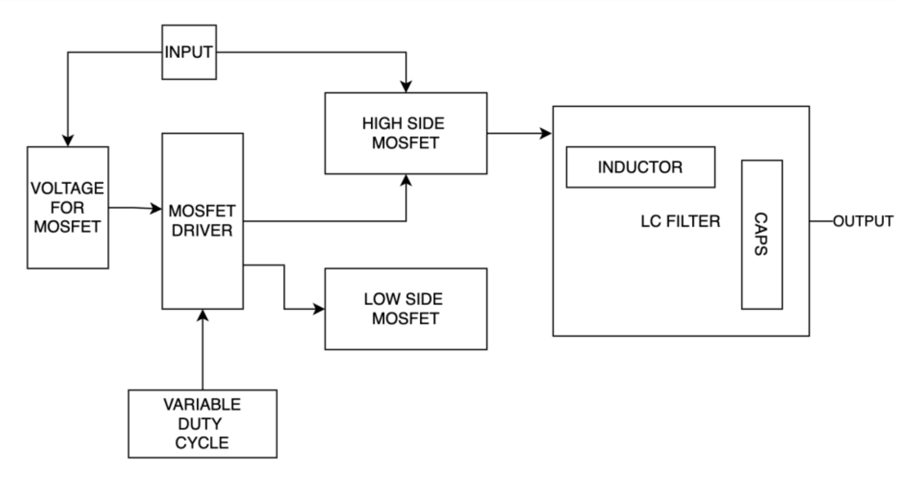

Fig.2. Design for Synchronous Buck Converter Design

In a synchronous buck converter, accurate control over the switching of the high-side and low-side MOSFETs is essential for efficient energy conversion. These switches alternately connect and disconnect the input voltage to the inductor, regulating the output through PWM (Pulse Width Modulation). Using a low-side MOSFET instead of a freewheeling diode significantly improves efficiency by minimizing conduction losses.

A crucial aspect of this dual-switch configuration is the introduction of a dead time, which is a short interval when both MOSFETs remain off. This prevents shoot-through—a condition where both switches conduct simultaneously, creating a direct short circuit across the supply, potentially damaging the components and reducing overall system reliability. Even a small overlap in switching can result in large current spikes, hence the dead time is vital for safe and reliable operation.

PWM Generation with Complementary Outputs and Dead Time Using STM8S003

The STM8S003F3P6TR microcontroller leverages its built-in 16-bit timer (TIM1) to generate precise high-frequency PWM signals, essential for efficient power conversion. Operating with an internal system clock of up to 16 MHz, TIM1 is configured to produce a 100 kHz switching frequency by carefully setting the prescaler (PSCR) and auto-reload (ARR) registers. The duty cycle is dynamically controlled through the compare register (CCR1), enabling accurate output voltage regulation.

To drive both high-side and low-side MOSFETs in a buck converter, TIM1 provides complementary PWM outputs (CH1 and CH1N). A programmable dead time is added via the DTG bits in the TIM1_BDTR register, introducing a short delay—typically around 10 ns—to prevent both switches from conducting at the same time. This avoids shoot-through and enhances system reliability. Table 1 demonstrates the embedded logic responsible for generating PWM and PWMN signals for switch MOSFETs

```
#include "stm8s.h"

void TIM1_PWM_Complementary_Init(uint16_t duty) {
   // Step 1: Configure PA2 (TIM1_CH1) and PA3 (TIM1_CH1N) as output
   GPIOA->DDR |= (1 << 2) | (1 << 3);   // Set PA2, PA3 as output
   GPIOA->CR1 |= (1 << 2) | (1 << 3);   // Push-pull
   GPIOA->CR2 |= (1 << 2) | (1 << 3);   // Fast mode

   // Step 2: Enable TIM1 clock
   CLK->PCKENR2 |= (1 << 7);  // Enable TIM1 peripheral clock

   // Step 3: Configure TIM1 for 100kHz PWM (16MHz / (1 * (159 + 1)) = 100kHz)
   TIM1->PSCRH = 0x00;
   TIM1->PSCRL = 0x00;        // Prescaler = 1
   TIM1->ARRH  = (159 >> 8);  // Auto-reload = 159
   TIM1->ARRL  = (159 & 0xFF);

   // Step 4: Set duty cycle
   TIM1->CCR1H = (duty >> 8);
   TIM1->CCR1L = (duty & 0xFF);

   // Step 5: Set PWM mode 1 on CH1 (OC1M = 110), enable preload
   TIM1->CCMR1 = 0x68; // OC1M = 110 (PWM1), OC1PE = 1

   // Step 6: Enable CH1 and CH1N outputs
   TIM1->CCER1 = 0x33; // CC1E = 1, CC1P = 0 (active high), CC1NE = 1, CC1NP = 0

   // Step 7: Set dead time (DTG bits)
   // For ~10ns at 16MHz = 0.16 counts. Nearest is 1 count = 62.5ns
   TIM1->BDTR = 0x81;  // MOE = 1 (Main output enable), DTG = 0x01 (minimal dead time)

   // Step 8: Enable auto-reload preload and generate update event
   TIM1->CR1 |= (1 << 7);     // ARPE = 1
   TIM1->EGR |= 1;            // UG = 1 (update registers)
```

```
    // Step 9: Enable counter
    TIM1->CR1 |= 1;          // CEN = 1
}
```

Table. 1: generating PWM and PWMN signals for switch MOSFETs

The duty variable can be dynamically modified by reading the analog voltage from a potentiometer using the ADC, or by receiving control values over a UART interface, enabling real-time adjustment of the output voltage.

To reduce overall system cost without sacrificing performance, a discrete BJT-based gate driver circuit has been designed as an alternative to conventional driver ICs such as the IR2110. This solution effectively drives both the high-side and low-side MOSFETs used in the buck converter topology.

High-Side Driver: The high-side gate is driven using a bootstrap configuration composed of BC547 (NPN) and BC557 (PNP) bipolar junction transistors. A 0.1 μF bootstrap capacitor, in conjunction with a resistor network (10 kΩ and 1 kΩ), helps elevate the gate voltage above the source potential. This ensures rapid turn-on of the high-side N-channel MOSFET (IRF540N), even when its source floats above ground as shown in Fig.3..

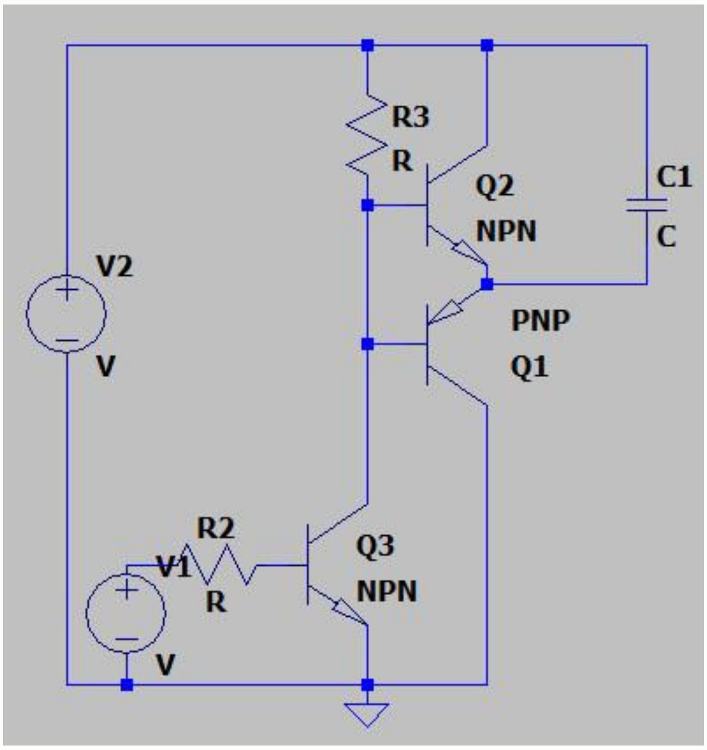

Fig.3. MOSFET Driver equivalent for high-side mosfet

Low-Side Driver: The low-side gate driver is implemented using a BC557 PNP transistor paired with a 1 kΩ pull-down resistor. This setup ensures fast gate discharge during turn-off events, enabling sharper transitions and improving overall switching efficiency—particularly important for synchronous rectification applications.

The switching of High-Side Driver and Low-Side Driver has been shown in Fig.7.

This compact and economical gate driving approach delivers fast switching characteristics, achieving rise and fall times below 50 ns as shown in Fig.6. As a result, the performance remains comparable to that of commercial gate driver ICs, but with a significantly reduced bill of materials (BOM) cost.

In a buck converter, the inductor and output capacitor are critical components that directly influence the efficiency, stability, and output voltage ripple of the system. The inductor smooths the pulsating current from the switching MOSFET and stores energy during the ON cycle, releasing it during the OFF cycle. A poorly chosen inductor can lead to excessive current ripple, reduced efficiency, or even instability. The value of the inductor L is calculated based on the desired current ripple I_L, input voltage V_in, output voltage V_out, switching frequency f_sw, and duty cycle D, using the formula:

$$L = (V\_in - V\_out) \times D \div (\Delta I\_L \times f\_sw)$$

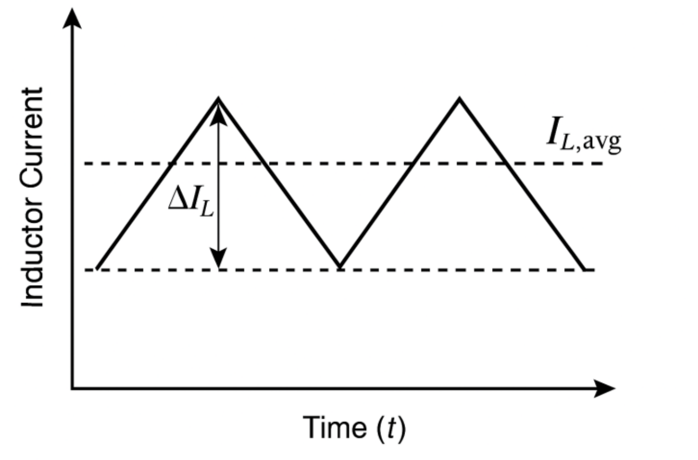

Fig.4. Inductor current and Ripple current of Inductor

Similarly, the output capacitor is responsible for minimizing output voltage ripple and providing immediate current to the load during switching transients. The required capacitance C_out can be approximated using:

C_out = I_out × D ÷ (ΔV_out × f_sw)

where ΔV_out is the allowable voltage ripple. Using low-ESR (Equivalent Series Resistance) capacitors further reduces voltage spikes and improves response time. Together, a well-matched inductor and capacitor ensure continuous conduction mode (CCM), low EMI, and high efficiency, which are essential for reliable operation in high-performance power supplies.

For the present design, which steps down 24 V to 12 V at 3 A with a 100 kHz switching frequency, the selected passive components ensure stable operation under continuous conduction mode (CCM). A 47 µH inductor is chosen to limit the peak-to-peak current ripple (ΔIL) to approximately 0.9 A (30% of 3 A), which helps reduce core losses and improves EMI performance. To prevent magnetic saturation under full-load conditions, the inductor features a saturation current rating of at least 4.5 A, ensuring safe operation during transient loads or startup conditions.

The output stage incorporates a 470 µF low-ESR electrolytic capacitor, complemented by a 10 µF ceramic capacitor to effectively suppress high-frequency switching noise. These values limit the output voltage ripple (ΔV_out) to below 120 mV, or 1% of the nominal output. The ceramic capacitor, with its low equivalent series inductance (ESL), helps filter high-frequency transients, while the bulk capacitor provides energy buffering during load steps. The careful selection of these components guarantees smooth inductor current waveforms and minimal voltage ripple across a wide range of loads, which is essential when powering precision analog or digital circuits. The resulting ripple current waveform remains triangular, centered around the average load current, and avoids saturation or discontinuous conduction even during fast transient conditions.

Wi-Fi Integration

To enable remote and dynamic control of the PWM duty cycle in real time, a Wi-Fi-enabled communication interface was implemented using the ESP8266 module in conjunction with the STM8S003F3P6TR microcontroller. This wireless interface allows users to interact with the buck converter system through a standard web-based interface or any client capable of making HTTP requests.

The ESP8266 operates as a local Wi-Fi server on port 80, hosting a basic listener that captures HTTP GET requests containing the desired PWM duty cycle value. When a request containing the keyword duty= is received, the module extracts the numerical duty value and transmits it via UART at 9600 bps to the STM8S.

```
#include <ESP8266WiFi.h>

const char* ssid = "YourSSID";
const char* password = "YourPassword";

WiFiServer server(80);

void setup() {
  Serial.begin(9600);  // UART to STM8S
  WiFi.begin(ssid, password);
  while (WiFi.status() != WL_CONNECTED) delay(500);
  server.begin();
}

void loop() {
  WiFiClient client = server.available();
  if (client) {
    String request = client.readStringUntil('\n');
    if (request.indexOf("duty=") >= 0) {
      int duty = request.substring(request.indexOf("duty=") + 5).toInt();
      Serial.write(duty); // Send duty cycle byte to STM8S
      client.println("Duty cycle sent to STM8S: " + String(duty));
    }
    client.stop();
  }
}
```

Table.2. Demonstrates the code for ESP8266 to connect to WIFI and Communicates with STM8S using UART

On the microcontroller side, the STM8S003F3P6TR is configured to receive UART data using USART1 in interrupt-driven mode. The UART receive interrupt (UART1_RX_IRQHandler) captures the incoming duty cycle byte and directly updates the TIM1 capture/compare register (TIM1_CCR1L), which controls the duty cycle of the complementary PWM outputs. The UART initialization ensures stable operation at the chosen baud rate with both transmitter and receiver enabled, along with receive interrupts for efficient and non-blocking communication.

```
void uart_init() {
   UART1->BRR2 = 0x0B;
   UART1->BRR1 = 0x08;     // 9600 baud @ 16 MHz
   UART1->CR2 |= UART1_CR2_REN | UART1_CR2_RIEN | UART1_CR2_TEN;
}

volatile uint8_t duty = 80;

@far @interrupt void UART1_RX_IRQHandler(void) {
   if (UART1->SR & UART1_SR_RXNE) {
      duty = UART1->DR;
      TIM1->CCR1H = 0;
      TIM1->CCR1L = duty; // Update duty cycle
   }
}
```

Table.3. Demonstrates the code for STM8 Communicating with ESP8266 using UART and receive duty cycle

This approach eliminates the need for manual reprogramming or analog control interfaces by enabling over-the-air tuning of PWM parameters. Such a method enhances the adaptability and interactivity of the converter system, making it suitable for use in IoT-based power regulation applications or educational experimentation platforms.

Closed-Loop Control Using ADC for Adaptive Regulation

In power electronics, particularly in DC-DC buck converters, maintaining a stable output voltage under varying load and input conditions is essential for performance and reliability. To achieve this, a closed-loop control system is implemented using feedback from the converter's input and output.

The STM8S003F3P6TR microcontroller, with its integrated 10-bit analog-to-digital converter (ADC), enables precise real-time monitoring of critical analog signals such as input voltage, output voltage, and output current. This allows the system to dynamically adjust the PWM duty cycle, ensuring that the output voltage remains within tight regulation limits, even in the presence of disturbances.

By sampling the output voltage and comparing it against a reference, the firmware increases or decreases the duty cycle of the PWM signal generated via TIM1, thus creating an adaptive, closed-loop system. This greatly enhances the efficiency, stability, and accuracy of the converter, especially for sensitive or dynamic loads.

```
#include "stm8s.h"

// Initialize ADC on Channel 3 (PC3 = AIN3)
void adc_init(void) {
   ADC1->CSR = ADC1_CSR_CH3;    // Select channel 3
   ADC1->CR1 = ADC1_CR1_ADON;   // Enable ADC
   ADC1->CR2 = 0x00;            // Right-aligned result
}
```

```
// Read 10-bit ADC value (0–1023)
uint16_t adc_read(void) {
   ADC1->CR1 |= ADC1_CR1_ADON;          // Start conversion
   while (!(ADC1->CSR & ADC1_CSR_EOC));  // Wait for end of conversion
   return (ADC1->DRH << 2) | (ADC1->DRL >> 6);  // Combine 10-bit result
}
```

Table.4. Demonstrates the code for generating feedback using ADC

III. RESULT AND ANALYSIS

To evaluate the performance and reliability of the proposed synchronous buck converter, an extensive series of tests were conducted under controlled laboratory conditions. The test environment consisted of an adjustable DC power supply (8 V to 24 V), programmable electronic load (0 A to 3 A), digital storage oscilloscope (100 MHz), and precision multimeters. The converter's core control was managed by the STM8S003F3P6TR microcontroller, which handled PWM generation, ADC sampling, and UART communication with the ESP8266 Wi-Fi module. A mobile application interface allowed real-time adjustment of duty cycle parameters through HTTP-based commands over Wi-Fi.

The key performance metrics observed during testing included:

- Input and Output Voltages (Vin, Vout)
- Input and Output Currents (Iin, Iout)
- PWM Duty Cycle
- Output Voltage Ripple (ΔVout)
- Inductor Current Ripple (ΔIL)
- System Efficiency (η)
- Transient Response to Load and Line Variations
- Thermal Characteristics of Switching Devices

Measurement points were selected at the input terminals, switching node, inductor, and output capacitor to ensure accurate waveform and DC level analysis. Ripple voltages were recorded using an oscilloscope in AC-coupled mode across low-ESR capacitors.

Output Regulation and Efficiency

The converter demonstrated excellent voltage regulation and high efficiency across varying input voltages and output load conditions. Table 5 summarizes the recorded data:

Input Voltage V_in (V)	Duty Cycle D (%)	Output Voltage V_out (V)	Output Current I_out (A)	Voltage Ripple ΔV_out (mV)	η (%)
24	90	21.6	2.5	62	93.4
24	80	19.2	2.3	58	92
24	70	16.8	2.1	55	91.1
24	60	14.4	2	51	90.6
24	50	11.9	1	42	92.3
24	40	9.5	0.7	38	90

Input Voltage V_in (V)	Duty Cycle D (%)	Output Voltage V_out (V)	Output Current I_out (A)	Voltage Ripple ΔV_out (mV)	η (%)
24	30	7.3	0.5	35	89.6
24	20	4.8	0.3	32	87.1
24	10	2.4	0.2	26	85.2
18	90	16.2	2.3	60	92.7
18	80	14.4	2.1	54	91.2
18	70	12.5	2	48	90.7
18	60	10.9	1.8	43	89.9
18	50	9.2	1.2	40	90.3
18	40	7.3	0.9	35	88.2
18	30	5.4	0.6	32	87.1
18	20	3.5	0.3	29	86.4
18	10	1.8	0.1	23	84
12	90	10.8	3	74	88.2
12	80	9.6	2.7	66	87.5
12	70	8.4	2.4	60	86.9
12	60	7.2	2	55	85.6
12	50	6	1.5	48	85.6
12	40	4.8	1.1	43	84.2
12	30	3.6	0.8	42	82.3
12	20	2.4	0.5	35	80
12	10	1.2	0.3	25	79
10	90	9.1	2.5	65	85.4
10	80	8	2.1	60	84.2
10	70	7	1.8	56	83
10	60	6	1.4	50	82.1
10	50	5	1	39	83.1
10	40	4	0.8	35	81.2
10	30	3	0.6	30	80
10	20	2	0.4	27	78.4
10	10	1	0.2	21	77.8
8	90	7.2	2	58	84.1
8	80	6.4	1.8	52	83
8	70	5.6	1.5	47	82.1
8	60	4.8	1.2	42	81
8	50	4	0.9	36	79.4
8	40	3.2	0.7	31	78.1
8	30	2.4	0.5	28	76.9
8	20	1.6	0.3	24	75.2
8	10	0.8	0.1	18	73
15	90	13.5	1.8	62	88.3

Input Voltage V_in (V)	Duty Cycle D (%)	Output Voltage V_out (V)	Output Current I_out (A)	Voltage Ripple ΔV_out (mV)	η (%)
15	70	10.5	1.5	51	87.1
15	50	7.5	1.2	44	86
15	30	4.5	0.7	36	84.2
15	10	1.5	0.2	22	81.6

Table 5. Recorded data from testing the system

Transient and Line Regulation

Load Step Test (1 A to 3 A): Output voltage dipped by 180 mV and recovered within 150 µs.

Line Step Test (18 V to 24 V): Output voltage remained stable, showing a maximum overshoot of 200 mV.

No-Load to Full-Load Behavior: Output voltage deviation remained within 2 % of the nominal value.

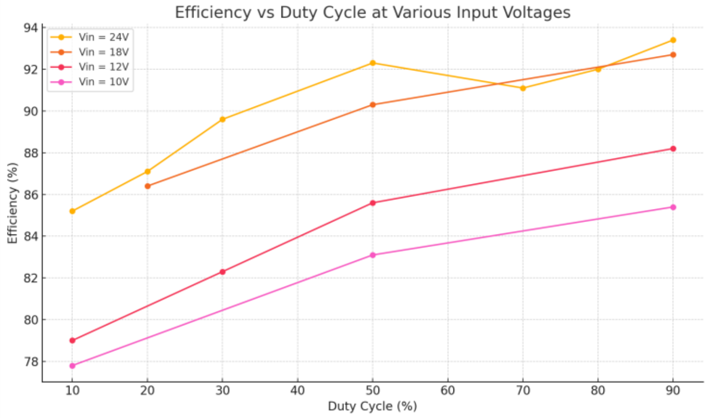

Fig. 5. Duty cycle vs Efficiency

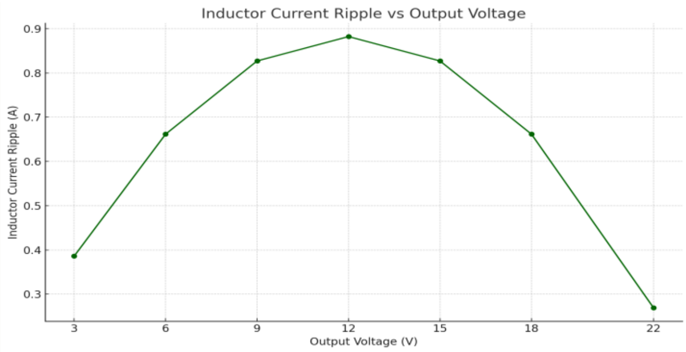

Fig.6. Output Voltage vs Inductor Current Ripple

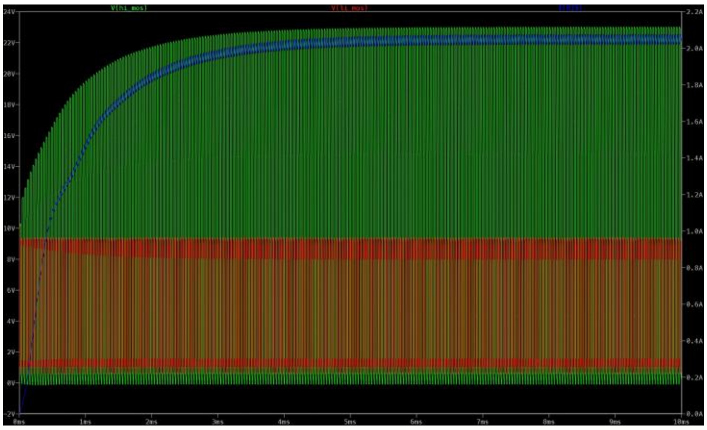

Fig.7. Green : High side MOSFET Switching

Red: Low Side mosfet Switching and
Blue: Output Voltage

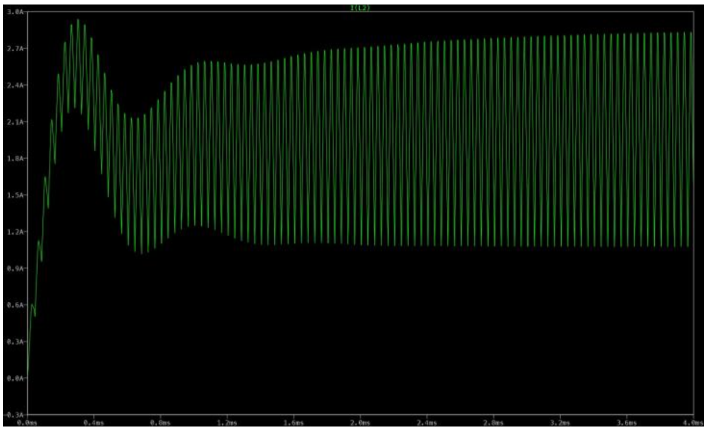

Fig.8. Inductor Current and Current Ripples for extreme load condition

Closed-Loop ADC Feedback Response

A key feature of this design is the inclusion of a 10-bit ADC feedback system. Voltage and current readings from both input and output stages were sampled continuously and filtered using software averaging techniques. Based on these real-time measurements, the duty cycle was automatically adjusted to maintain output stability even under varying load or line conditions. The precision of the ADC allowed regulation within ±100 mV of the target output voltage under all tested conditions.

Thermal and Stability Observations

Under full load (3 A) and continuous operation, the high-side and low-side MOSFETs reached a maximum temperature of ~42°C without heatsinks. With minimal passive heat sinking, the temperature was contained under 35°C, indicating low switching losses and efficient thermal dissipation.

IV. CONCLUSION

This study presents a comprehensive approach to the development of a smart, digitally controlled synchronous buck converter that integrates wireless communication for enhanced functionality. The converter, built around the STM8S003F3P6TR microcontroller and the ESP8266 Wi-Fi module, offers adjustable output control through a web-based interface, enabling flexible operation suited to modern embedded and IoT applications.

Experimental evaluation of the system across a wide duty cycle range—from 10% to 90%—demonstrates stable performance, with output voltages tracking the reference inputs accurately. The use of a 68 μH inductor and appropriately selected output capacitors ensures low ripple and consistent current flow, while the 10-bit ADC on the STM8S provides real-time feedback for voltage and current monitoring. This enables the system to act as a closed-loop controller, dynamically adjusting the PWM duty cycle in response to input and output conditions.

Efficiency measurements confirm the converter maintains high performance, peaking at over 92% under optimal conditions. The findings affirm the converter's suitability for applications where compact design, energy efficiency, and remote configurability are essential. Further research can extend this foundation by incorporating advanced control algorithms, integrating energy monitoring features, and enabling cloud connectivity for industrial and educational uses.

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Some Studies on Automatic Dam Water Level Monitor and River/Canal Gate Opening Control System

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ABSTRACT

The prime objectives of dam erection are for various common people's benefits, such as flood water control, water supply for drinking & other uses, irrigation & agricultural use for cultivated land, river bed sedimentation control, cheapest hydropower generation, navigation, etc. The basic need of a dam is to maintain an adequate water level for optimal & efficient management of water resources for a particular river in a particular geographic location, considering seasonal variation of weather parameters. A digital distributed control scheme is proposed for dam gate control in place of conventional & existing manual control schemes for better management of rivers & canals.

This paper presents a novel scheme to employ a Gateway commensurate with remote control via industrial-grade hardware from the local control centre through IEC60870-5-101/104 protocol, fetching data from a statistical environment. The water distribution management is controlled & monitored by sensing signals with transducers, processing them and sending actuating signals towards control valves for water flow control according to system requirements.

Keywords: Digital Distributed Control, Gateway, Sensors, Control Valve, Server.

I. INTRODUCTION

Dams have been erected recently for multidisciplinary activities and flood control uses. So, it requires constant vigil by applying the latest instrumentation & IoT-based monitoring system. In the case of existing manual control, especially in the present-day fluctuating weather, it is not possible to fine-tune the dam control system. As a result, it causes dissatisfaction, casualties, and financial losses to people in subsequent political unrest in an affected state/state. The following scheme is proposed to address this issue.

For water resource management, advanced approaches like Arduino microcontrollers are employed for dam automation projects. Manual intervention & periodic inspections of dams, in addition to limited real-time monitoring & response capabilities, are the basic criteria for conventional dam management. The application Arduino for advanced automation technologies has radically transformed the dam level controller by enabling data acquisition & control through remote monitoring techniques. The basic advantages of Arduino are that it is user-friendly & has various applications for automation in various fields/utilities, including dam management techniques.

The available literature on dam management reveals that Arduino has many applications for dam water control systems. It can be applied for dam water level observation associated with gate valve control, improving overall operational efficiency, enhancing safety & security and optimizing available primary inputs used for reservoir management. [1,2] Despite this advanced progress, it can be found that major gaps in research are observed for real-time predictive maintenance, especially in the field of advanced optimal control algorithms & integration of advanced machine learning techniques, design & development. Much research is going on for dam automation using Arduino; they have made tremendous progress & made the system more efficient, resilient & sustainable for water resource management. Dam gate level monitoring and control -This paper mainly narrates IoT (Internet of Things) applications for water level controllers in a dam. It elaborates on the unique use of IoT for the design, implementation & control of programme observation systems. The primary operation of the automatic gate control arrangement under minimum water level conditions for various climate situations is based on statistical data. [3,4]. The basic need for dam control is the automatic opening and closing of the gate, which is an essential feature for Dam Management. This auto control mainly relies upon different categories of system control elements. Detailed project design & implementation were done by Zeyanna et al. (2017), who elaborated on an exhaustive concept about the erection & commissioning of the proposed system using solid-state electronic devices. An automatic water level monitoring & control system could sense the up/down in water & act accordingly. It will save manpower, reduce risk, and provide safety for people and habitats. The wireless communication system is mainly used with enormous opportunities for satellite communication [5].

[6] proposes a dam monitoring system which considers safety and water management as parameters, briefing those as extremely important for starvation and surplus of water conditions; the basic concept of the project narrates the application of IoT in Dam water management, and the said system concentrates on storing and retrieving the information from/to the cloud, it utilizes vibration sensor and ultrasonic sensor to find major changes of parameter in the dam and highlights the same. [6] provides elaborate planning for the improvement of an information system based on the conventional systems in practice with the application of sensors and IoT; it also gives a proposal for procuring and apportioning live data records about the hydro levels to the system administrator of the dam, based on the available real-time data administrator could take a conclusion to open or shutting the gates. [7] Based on ASP.NET technology, this paper gives a development concept of a desegregated observation engine for water, a comprehensive mechanism of the hydro observation platform, and conceptualises the overall control feature of a dam water-watching platform. A basic reservoir dam monitoring system has been conceptualized in this project to improve the overall system's emergency response capability. The stated system contains Web management, data acquisition, and database. The project proposes a basic to discuss possibilities of IoT applications & implications in Dam Safety and water management. Here, various sensors sense the total dam and the main

pipeline in real-time. The wireless sensor points are interconnected and transmit the data to a gateway. A common storage space/Data Centre is a database store that caters to the observer's online information.[8] gives a proposal for implementing an information system based on conventional systems with some sensors and IoT applications. In this paper, an automatic system is tabled, and if the dam water level is raised above a predetermined set point, alarming messages will be transmitted to the mobile numbers. [9] highlights how to reduce the bottlenecks faced by Dam authorities for the manual operation of gates; the primary concept of this project is to build a website which will keep records and provide true online data for dam control parameters & associated weather such as vibration, temperature, humidity, dam level, gate position, rainfall etc. The uniqueness of this system is that it introduces GUI Software. While running, this software has two advantages: autopilot mode and manual data mode. Behind the curtain of the software, it takes live parameter information from the concerned sensors and then shares it with the database. The database is then reproduced on a web portal, and further decision-making is based on available data if it is required to be taken by appropriate authorities.

India is facing many problems with the water crisis due to climate change, silting, improper functioning of dams, insufficient water-saving systems, etc. [10]. It has been found that maximum trouble arises due to the malfunction of the gate valve, which is not commensurate with the dam water level. However, a proper signal is available from the dam controller. A manual mode of control is also available for some dams. While operating in manual mode, there are some challenges associated with it. It is almost impossible to manually open or close the gates in a heavy flood due to huge rainfall or uncertain weather. Regulating the dam gate valves for water level management is very much required by implementing an automatic control scheme, especially in full reservoir conditions [11]. Manual control takes a lot of time, and it is not safe for the dam management system. It is possible to inform the common public within the vicinity by buzzer and advanced preventive measures & precautions according to system requirements, utilising an auto control unit as per the alert signal received by the competent authorities. It is easier to detect cracks in a dam by using an Ultrasonic Crack Detector [12]. Much research has already been done to monitor hydro levels & control dam-related gates. Some of the above-related remarkable research works are narrated below:

A. IoT-based water supply monitoring and control

Human civilization depends on the water available in the locality, which is a basic & essential need for everyone. Everyone needs to save water to keep civilisation in progress. Sometimes, it can be seen that the waste of water happens due to a lack of monitoring & consciousness. Huge amounts of water are wasted due to spills from tanks. In the case of water pipelines, it is observed that due to high-pressure cracks/leaks, total damage ultimately occurs. Sometimes, it isn't easy to detect it. Lack of monitoring, application of manual labour, and engagement of less manpower are all contributing factors to the failure of water pipelines. [13].

B. Automatic Gate & Reservoir Level Control using WSN technology

A dam is a barrier that preserves water in the associated reservoir. From the reservoir through flood gates, controlled water is dispatched to adjoining canals & irrigation lands as per the prescheduled program. If the water level in a dam is crossed at a safe level, there is every chance of the dam's gates failing. The dam level is continuously monitored to prevent this phenomenon. There is an urgent need to preserve quality water as it is scarce & valuable. An Analytical Instrument is used to monitor & continuously evaluate water parameters. All the indicative parameters, like impurities, temperature, pH values, etc., are measured in real-time. The theme of the paper is the round-the-clock monitoring of hydro height in the associated dam & flood alert system with the application of PIC16F877A Micro Controller [14].

C. Wireless Disaster Monitoring and Management System for Dams

The primary objective of this paper is the judicious use of IoT (Internet of Things) to control the water level in the dam. A unique design, implementation and control of the programmed monitoring system was developed for this specific project. IoT is the basic essence of the project. Specific case studies are done for the dry running conditions under various probable dam scenarios for automatic gate control operation to obtain the best results. The main work is to control the dam gate valve by observing weather parameters & reservoir level and to communicate online alert signals by developing an appropriate mechanism for it, which is the theme of the paper. There was a storm in June 2013 when heavy rainfall occurred due to a cloud burst in various places. Havoc damage to life & property is observed. The main reason is the lack of coordination of various dams, especially those not in unison with local weather parameters [15].

D. Dam gate level monitoring and control

The primary objective of this paper is the judicious use of IoT (Internet of Things) to control the water level in the dam. A unique design, implementation and control of the programmed monitoring system was developed for this specific project. IoT is the basic essence of the project. Specific case studies are done for the dry running conditions under various probable dam scenarios for automatic gate control operation to obtain the best results [16,17,18].

E. Arduino-Based Automatic Dam Monitoring and Alert System

These papers deal with the river where the dam is controlled through automation. SISO is a single-input & single-output system used in cascade form for the present system. SIMO, i.e. single input but multiple output system, may be utilized for the Dam monitoring & control system. The intermediate distributed measurement points may acquire multiple outputs along the river. IMC (Internal Model Controller) is developed using a generic robust design synthesis. Due to the nonlinear dynamics of the system, the resilience is approximated with a bound on multiplicative uncertainty, taking into account the model errors. Nonlinear model approximation validation of the river is carried out through simulations. To develop engineering methodologies for the establishment, the industry has always focused on modifying any meticulous process through easier automation methods. [19,20].

F. IoT-Based Lake Water Level Monitoring System

The uniqueness of this paper is that the lake water storage source for a village is monitored & controlled through automation. Raspberry Pi is a controller for wired & wireless water level measurement & control systems. It can also measure the water content in the lake. Here, GSM technology is used. High computation power & graphical user interface with high-quality cellular phone technology are available. It is essential in a mobile application to reuse such valuable resources from the user's perspective. Ultimately, this paper has proposed a service protocol for web and cellular-based monitoring of the water content in a lake [21].

II. PROPOSED METHODOLOGY

The main objectives of dams are constructed for specific purposes such as water supply, flood control, irrigation & agricultural use, navigation, sedimentation control, hydropower, etc. A dam is the cornerstone in the development and management of water resources development of a river basin. According to seasonal needs, the most important purpose of a dam is to hold & preserve water up to a safe level in its reservoir. One of the key issues is water distribution & utilization of the dam reservoir through efficient water management. For this, it is very much required to design a dam automation system to open & close the gate valves to maintain a safe water level in the reservoir to avoid hazards per water utilization requirements, e.g., irrigation, electricity generation, etc. Extensive research is going on for the betterment of safe utilisation of dams, optimum water flow & avoidance of gate corrosion through IoT applications. This paper intends to use Gateway for remote control via industrial-grade hardware from the local control centre through IEC60870-5-101/104 protocol for monitoring and controlling the water distribution management by using various sensors and control valves, automatically & proactively manage outflow during crisis by using statistical data of the environment.

The proposed scheme is like a pyramid structure, which consists of an Area River Control Centre (ARCC) for each river flowing in a State at a macro level under a State River Control Centre (SRCC) for each State. SRCCs will be controlled by the concerned Regional River Control Centre (RRCC). In India's five regions, namely Eastern, Western, Northern, Southern & North-Eastern, there will be five SRCCs. All five SRCCs will be ultimately governed by the National River Control Centre (NRCC). The unique advantage of this scheme is that in case of an outage or cyber-attack, a particular control centre next in the hierarchy will take control. This scheme is mainly designed for irrigation & agricultural use, Hydropower Generation & flood control. The river control scheme is shown in Figure 1.

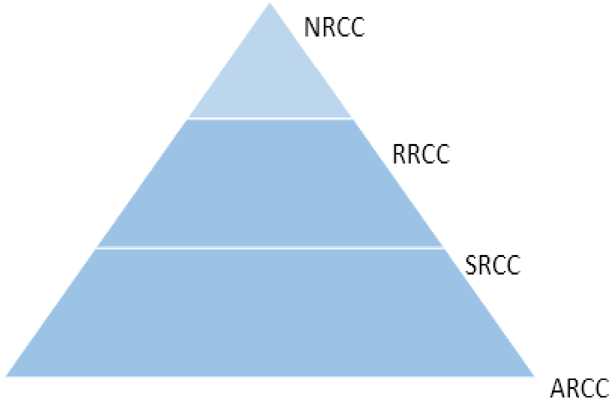

Figure 1: Schematic Diagram of River Control Centre

Data are taken from the agricultural field through Rain Sensor & Moisture Sensor, requirements from the Load Despatch Centre for the hydro generation to meet peak load or contingency, etc., from the dam for water level measurement through Ultrasonic Sensor, water level sensor, and the secondary signal from a vibration sensor, etc. In the case of a dam, two types of gate valves are used, viz. flood level control valve & irrigation cum power generation control valve. In the case of an irrigation canal, another canal control valve is used to control water flow for irrigation. Level Sensor is installed at the Minimum Safe level, the Safe level, & Maximum Safe level of the Dam Reservoir. A vibration sensor is installed at the maximum level of the dam to maintain a fail-safe system. Valve operation logic is designed in such a way that the flood level control valve will open when the water level is reached at maximum safe level & irrigation cum power generation control valve will open when the water level is above the minimum safe level according to the control signal available from irrigation water level control centre for irrigation water requirement & electrical load despatch centre for hydropower generation to meet electricity demand. The logic circuit for the irrigation cum power generation control valve will vary as per seasonal requirements.

In the summer season, the valve will open based on AND logic when irrigation & electricity demands are present simultaneously. In the case of the winter season, the valve will open based on OR logic when irrigation demand is predominant. Canal valve operation may be controlled per the irrigation water requirement in a particular area. In the monsoon season, the valve will open based on OR logic when electricity demand is predominant, as thermal units are taken out of the bus as per the prescheduled preventive maintenance program. While the valve is in open condition, the canal gate is kept closed to avoid excessive inrush of water in agricultural land. The flood level control valve will operate when the reservoir level exceeds the maximum safe level, along with a signal from the vibration sensor.

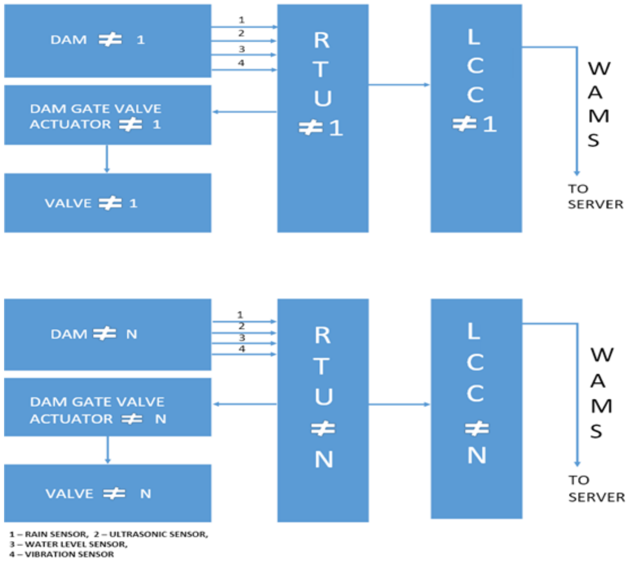

Figure 2: Dam Gate Valve Control Architecture

The vibration signal gets priority in comparison to the maximum safe level signal. In this situation, the canal control valve will be in close condition. All the alarm & valve actuator signals are set according to the design criteria of a particular reservoir. Here, a valve means a series of valves for a particular job.

In the case of the Dam Control Scheme (Fig. 2), Dam status Signals sensed from the Rain, Ultrasonic, water level & vibration sensors are processed through the Remote Terminal Unit (RTU) and sent to the Local Control Centre (LCC) for further processing & decision making by server & appropriate control signal is send to Dam Gate Valve Actuator to control the respective valve accordingly. There may be an N-number of Dams; each has an individual Dam Control Scheme, but all are connected to the same server.

In the case of Canal Gate Control Scheme Figure 3, various signals, e.g soil moisture, air humidity, air temperature, wind speed, etc, are fetched from the canal adjacent irrigation field station/stations & after processing in RTU, were transmitted to LCC through LAN for further transmission to a central server. After comparing the input signals with the set signals, the appropriate control signal from the server is sent to the Canal Gate Controller for opening & closing the valve. N-number Canal Gate Control Scheme may be linked with a particular Dam Gate Control Scheme/Schemes as per system design requirements.

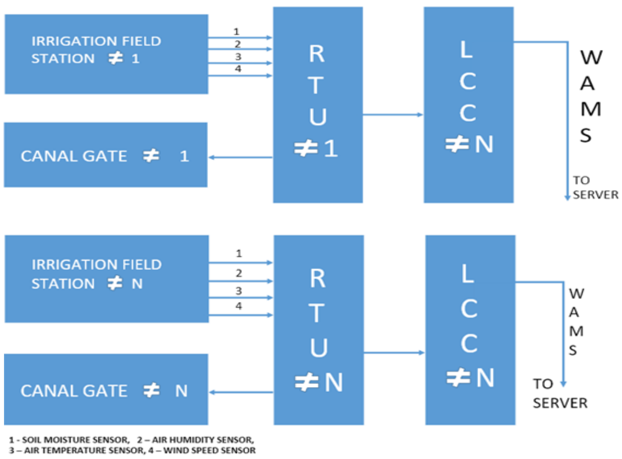

Figure 3: Architecture of Canal Gate Control

For further control through the Central Server, the backup Server is used for redundancy (Figure 4). Input/output signals for the server are fetched/sent from/to LCCs through the Wide Area Management

System (WAMS). Microwave links, optical fibre links, wire links, etc., may be used as WAMS mediums for signal transmission. Input signals are sensor output & output signals are Dam & Canal Valve Control signals.

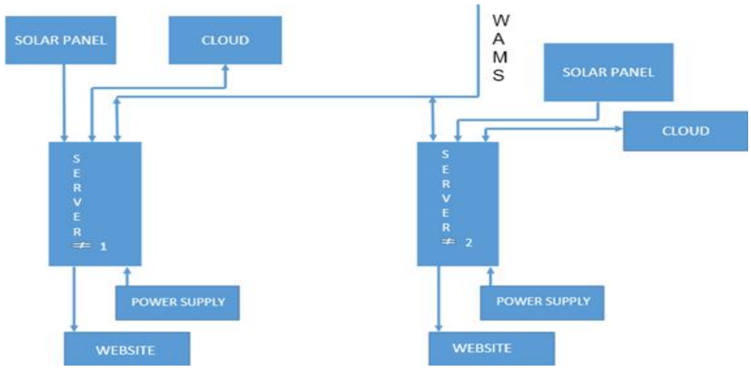

Figure 4: Server Panel architecture

In the case of Server backup, power is available from Solar Panel & associated Battery storage cum Inverter scheme. The server is linked to a dedicated website that continuously updates the related beneficiaries' present status for further processing. Sequence Event Recorder/Event Data Logger provision is available. It can also be a Supervisory Control & Data Acquisition System (SCADA) system. Cybersecurity is also provided to avert hackers' interference. Cloud sharing is also incorporated from a data security & redundancy point of view. It is possible through software to change the threshold level of input signals & Dam cum Canal control logic circuit. Software & Hardware development and validation program of the work-through model is in process.

III. ADVANTAGES OF RIVER CONTROL SCHEME

i. Error-free auto control compared to manual control.
ii. Minimum manpower required compared to manual mode operation.
iii. Multi-level hierarchical control.
iv. The minimum time is required for operation.
v. Used for multiple purposes, i.e., irrigation, power generation, flood & silt control, etc.
vi. User-friendly software.
vii. Quick recovery of the project cost.

IV. CONCLUSION

The proposed scheme can be entrusted for integrated & well-coordinated control of dams & canal control gates as per seasonal requirements. Such distributed control for the dam & canal will fulfil the multidisciplinary purpose of the proposed scheme & capitalisation of project cost within a short period. Its unique feature is continuous error check option for the total process is incorporated and total process control time is minimum compared to similar one in use. Power consumption for the total process is very much negligible.

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MediGeek – A Social Media App for Medical Professionals

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ABSTRACT

This project introduces Medigeek, a specialized social networking platform that aims to revolutionize professional interaction within the healthcare and medical community. Unlike generic networking platforms, Medigeek is purpose-built to meet the unique needs of medical professionals by combining social connectivity with clinical utility. The app allows users to create professional profiles highlighting qualifications, specialties, research, and clinical interests; connect with peers, mentors, and institutions; share insights on medical advancements; and stay updated with industry trends, conferences, and opportunities. Key features include secure peer-to-peer messaging, verified credential systems, CME (Continuing Medical Education) tracking, discussion forums by specialty, tele-collaboration tools, and job board integrations. The platform also promotes academic visibility through research publication sharing and citation tracking. Medigeek aspires to become the central hub for medical networking, continuing education, and professional growth, ultimately enhancing collaboration and improving patient outcomes globally.

Keywords: Research Paper, Technical Writing, Science, Engineering and Technology

I. INTRODUCTION

In the rapidly evolving healthcare landscape, the imperative for seamless connectivity, efficient collaboration, and continuous access to the latest professional insights has never been more pronounced. Medigeek emerges as a purpose-built social media platform meticulously crafted to address these critical needs for a diverse range of **Error! Reference source not found.** healthcare professionals, including doctors, n urses, specialists, researchers, and allied health practitioners. This innovative application provides a secure and dedicated digital environment where these professionals can seamlessly interact, readily exchange invaluable knowledge, and collectively contribute to the ongoing advancement of medical science and the enhancement of patient care outcomes.

At its core, Medigeek is thoughtfully engineered to cultivate a strong sense of community and facilitate robust **Error! Reference source not found.**collaboration among healthcare professionals spanning various m edical specialties, diverse clinical settings, and geographical boundaries. The platform boasts a comprehensive suite of tailored features specifically designed to streamline professional interactions and enable the efficient dissemination of crucial information. A dedicated chat room serves as a **Error! Reference s ource not found.Error! Reference source not found.**virtual hub for real-time communication, empowering users to engage in swift consultations with peers, delve into the intricacies of complex cases, and provide invaluable mutual support. Complementing this interactive space, the integrated job posting board functions as a vital resource for both **Error! Reference source not found.**healthcare professionals seeking new career o pportunities and healthcare institutions aiming to connect with qualified and dedicated talent within the sector.

To ensure that users remain consistently informed and actively engaged within the platform, Medigeek incorporates a sophisticated and user-friendly notification system. This intelligent system provides timely alerts regarding new direct messages received from colleagues, incoming friend requests from fellow professionals seeking to expand their networks, newly posted job opportunities that align with their expertise and interests, and important updates shared within their immediate professional circles and broader medical communities. Furthermore, the dynamic feed section serves as a central conduit for the dissemination of critical medical updates, **Error! Reference source not found.**insightful case studies drawn f rom real-world clinical experiences, groundbreaking research findings that are shaping the future of medicine, and thought-provoking perspectives shared by influential leaders and innovators within the healthcare arena. This continuous flow of relevant information actively promotes a culture of lifelong learning, encourages critical discussion and the exchange of diverse viewpoints, and empowers professionals to remain at the forefront of the latest medical advancements and best practices.

Recognizing the **Error! Reference source not found.**paramount importance of both security and user c onvenience within the sensitive healthcare domain, Medigeek employs a robust and multi-faceted authentication system. Leveraging industry-standard JSON Web Tokens (JWT), the platform ensures secure and reliable login and signup processes, effectively safeguarding sensitive user data and upholding stringent privacy standards. To further enhance user accessibility and streamline the initial onboarding experience for busy healthcare professionals, Medigeek also offers seamless integration with trusted third-party login providers, such as Google and Microsoft, allowing for a quick and efficient entry into the platform. Once successfully authenticated, users gain immediate access to a comprehensive suite of collaborative tools, empowering them to effortlessly share updates on their professional activities, engage in direct and secure messaging with individual colleagues, and actively participate in focused group discussions centered around specific medical specialties, cutting-edge research areas, or pressing clinical challenges.

Facilitating the development of meaningful and impactful **Error! Reference source not found.Error! Re ference source not found.**professional connections stands as a core objective of Medigeek. To this end, the platform incorporates an intuitive and user-friendly friend request system, enabling users to easily identify and connect with trusted colleagues, mentors, and peers, thereby expanding their professional network and fostering valuable relationships. Comprehensive and customizable user profiles provide a dedicated space for individuals to effectively showcase their **Error! Reference source not found.**professional qualifications, e xtensive clinical experience, specific research interests, and areas of specialized expertise, fostering transparency within the community and enabling the formation of relevant connections based on shared interests, complementary skills, or mutual professional needs. Users retain granular control over the information displayed on their profiles, with intuitive options to easily save changes, effectively manage their online professional presence, and, when necessary, securely delete their account. Ensuring the ongoing security of user accounts is also a top priority, with a straightforward and readily accessible logout functionality integrated throughout the platform.

II. METHODS AND MATERIAL

A. USE CASE DIAGRAM

Error! Reference source not found.A Use Case Diagram is a visual representation that illustrates the i nteractions between users (actors) and a system to achieve specific goals. It outlines the series of events and actions that occur when an actor uses a system, showing the system's functionality and how users interact with it.

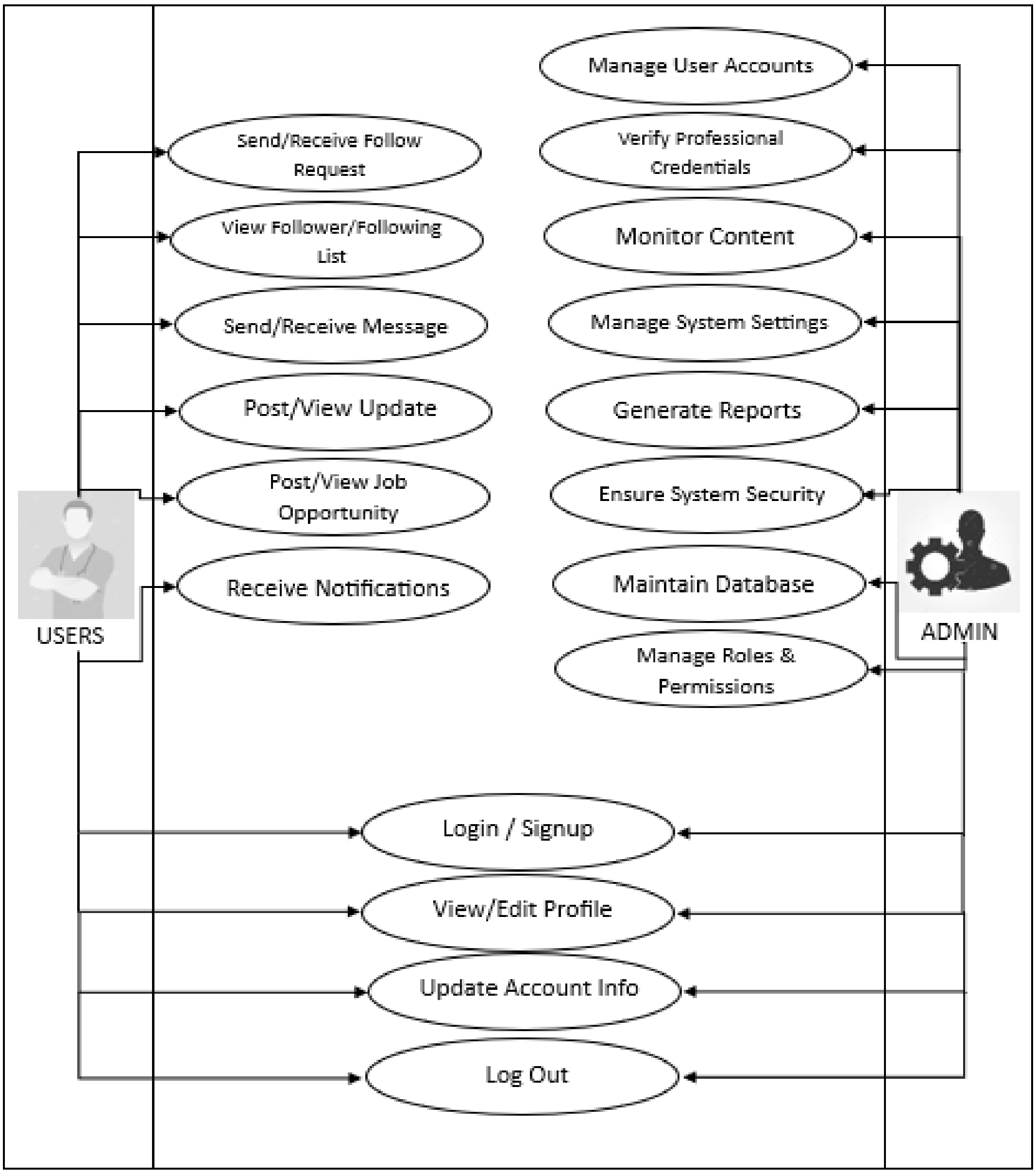

Fig 2.1: A use case diagram outlining the series of events and actions that occur when an actor uses a system.

B. DATA FLOW DIAGRAM

Error! Reference source not found.A Data Flow Diagram (DFD) is a graphical representation of the flow of i nformation in a system. It illustrates how data moves through a system, who or what processes the data, and where it is stored. DFDs help to visualize the sequence of activities and the relationships between them, making it easier to understand how a system works.

Level 0, also known as the Context Diagram, presents the entire system as a single process, showing only its interactions with external entities.

Level 1 DFD then decomposes this single process into its major sub-processes, revealing the system's primary functional components.

It illustrates the data flow between these sub-processes, as well as their connections to external entities and initial data stores.

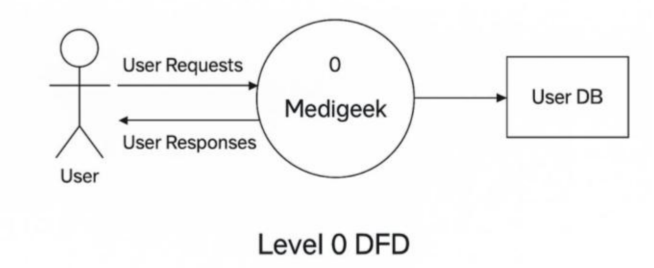

Fig 2.2: Level 0 DFD - Showing the entire system as one process and its data exchange with external entities, defining the system's scope.

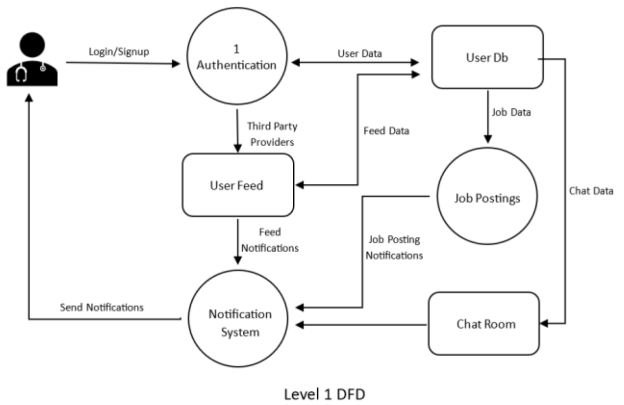

Fig 2.3: Level 1 DFD - A data flow diagram visualizing the sequence of activities and the relationships between them.

C. ENTITY RELATIONSHIP DIAGRAM

Error! Reference source not found. An Entity-Relationship Diagram (ERD) is a type of structural diagram u sed in database design. It illustrates the relationships between entities (things) in a database. ERDs help in visualizing and understanding how data is organized and connected, making them crucial for designing efficient and effective databases.

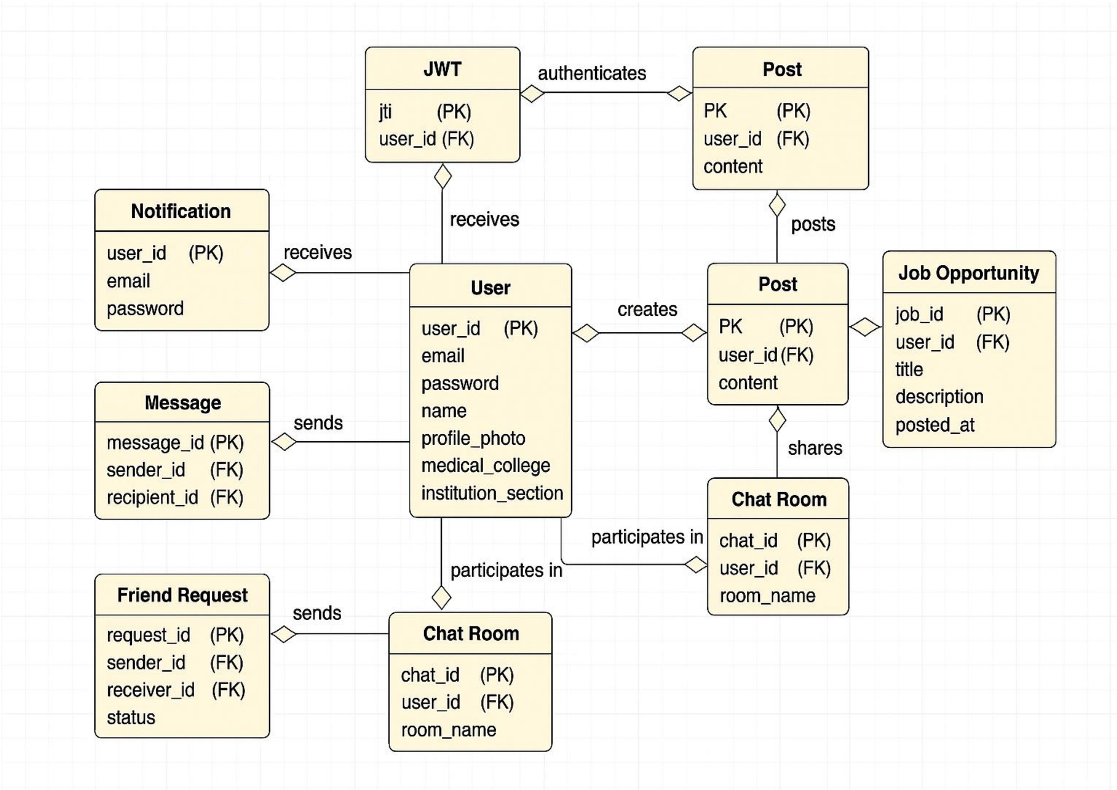

Fig 2.4: An entity relationship diagram visualizing and understanding how data is organized and connected.

III. RESULTS AND DISCUSSION

GRAPHICAL USER INTERFACE

Landing Page:

The Medigeek landing page cleanly showcases its core features: community exploration, highlighting networking and connection possibilities; job opportunities, with easy access to listings and career advancement; and skill assessments, emphasizing professional development and validation. The professional layout uses clear visuals and calls to action to quickly convey these key benefits to healthcare professionals, encouraging them to explore and register for the platform's networking, career, and skill-building resources.

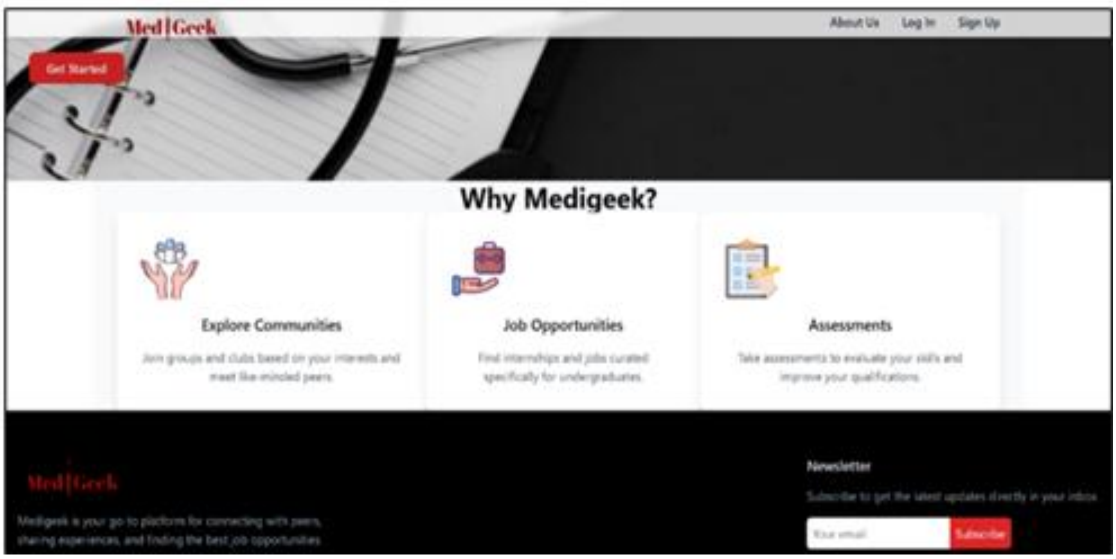

Fig 3.1: Visuals of the Landing Page

Login Page:

Medigeek's login page offers a modern interface with clearly defined fields for username and password, ensuring ease of access. The vibrant, tech-inspired background likely incorporates dynamic patterns or gradients, creating a visually engaging and contemporary feel. This design aims to project innovation and professionalism, providing a welcoming yet secure entry point for healthcare professionals to access the platform's collaborative resources.

Fig 3.2: Visuals of the Login Page

Home Page:

The Medigeek home page acts as the central hub, presenting a continuous and easily navigable feed of relevant information. This streamlined, scrollable format ensures healthcare professionals can effortlessly stay updated on posts from their network, important medical updates, job postings, and user interactions. The feed likely prioritizes key information, potentially using algorithms to highlight relevant content. User interactions, such as likes and comments, are seamlessly integrated within each post, fostering engagement directly within the central feed.

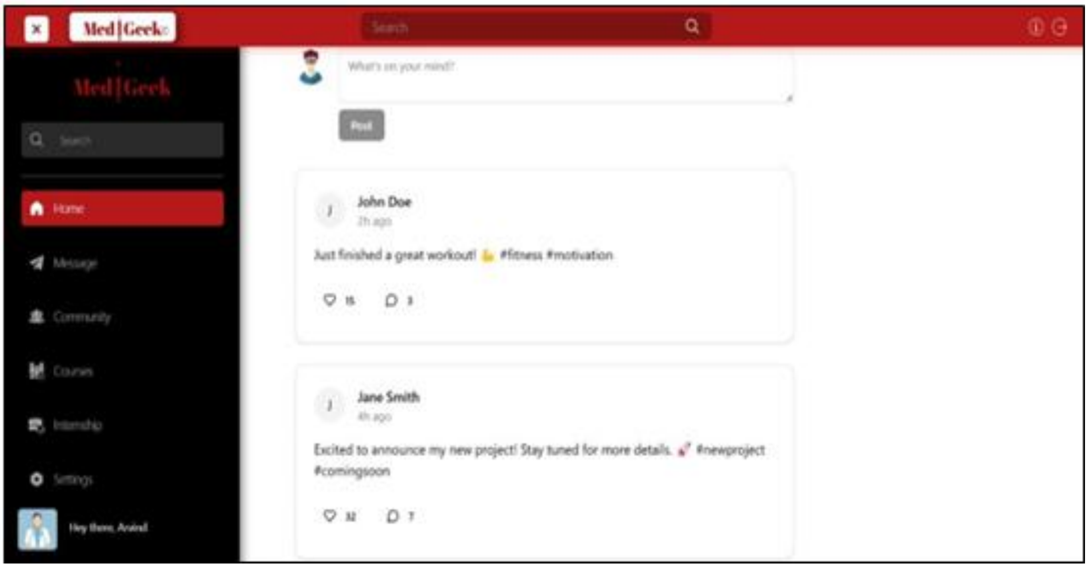

Fig 3.3: Visuals of the Home page.

Settings Page:

Medigeek's settings page offers a user-friendly experience for account management. With a simple and clean layout, healthcare professionals can easily update personal details, securely change their passwords, and customize their account preferences. This intuitive design ensures effortless control over their profile and privacy settings, promoting a seamless and secure user experience within the platform.

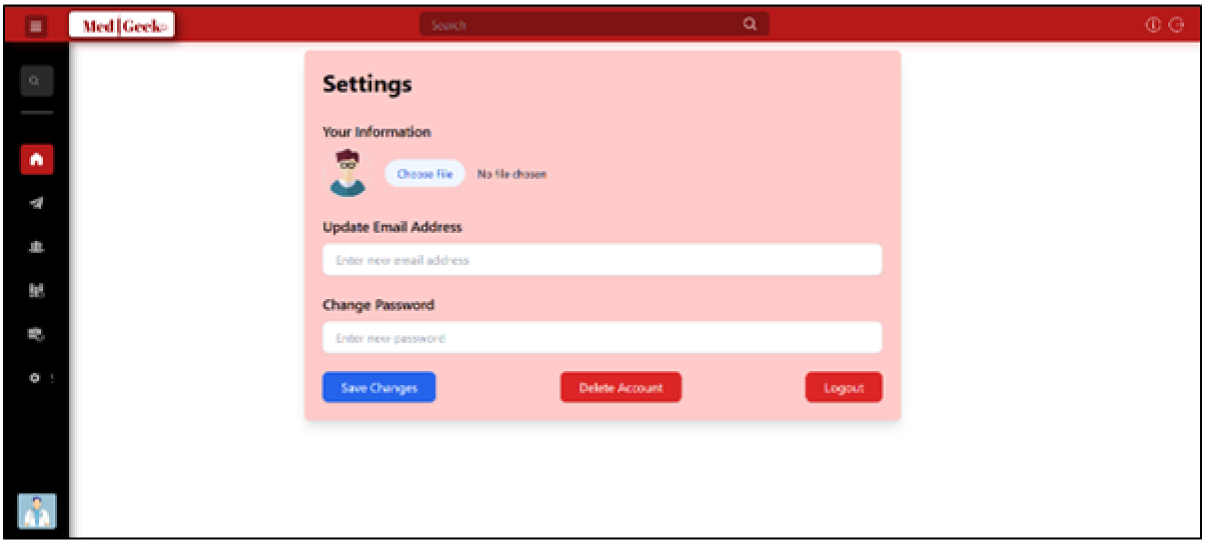

Fig 3.4: Visuals of the Settings Page.

Chat Room:

Medigeek's chat room enables immediate real-time communication between healthcare professionals. Its intuitive sidebar interface allows users to easily navigate and manage multiple ongoing conversations simultaneously. This design fosters quick connections and facilitates efficient information exchange among users within the platform's collaborative environment.

Fig 3.5: Visuals of the Chat Room.

Jobs Section:

Medigeek's jobs section is designed to streamline the career exploration process for healthcare professionals. It offers personalized job recommendations, likely based on user profiles, skills, and preferences, ensuring relevant opportunities are highlighted. Alongside each listing, clear application options are provided, simplifying the process of expressing interest and submitting applications directly through the platform. This user-centric design aims to make it easy for doctors and other healthcare experts to discover and pursue suitable career advancements within the Medigeek ecosystem, saving them time and effort in their job search.

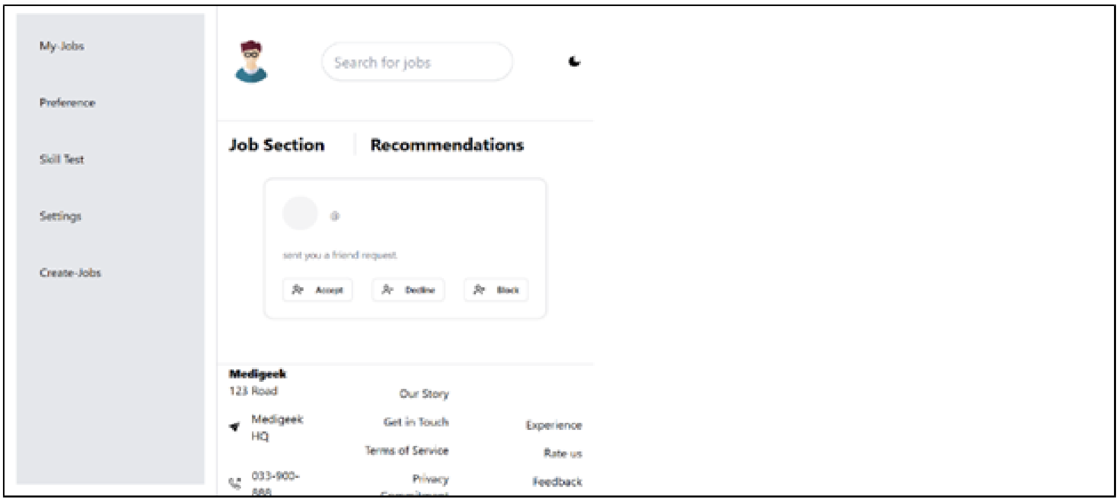

Fig 3.6: Visuals of the Jobs Section.

Profile Section:

Medigeek's profile section offers a concise yet comprehensive overview of a healthcare professional's identity and engagement. The bio provides a brief summary of their expertise and interests. The follower count indicates their network size and influence within the community. Recent posts offer a glimpse into their contributions, shared knowledge, and activity on the platform. Together, these elements provide a quick snapshot of a user's professional presence and engagement within the Medigeek ecosystem.

Fig 3.7: Visuals of the Profile Section.

Admin Dashboard:

The Medigeek admin dashboard provides a centralized hub for platform management, offering key insights into user activity. The overview of user engagement likely displays metrics like active users, new registrations, and community interaction levels. Login history allows administrators to monitor access patterns and ensure security. Content statistics offer data on post frequency, popular topics, and overall content contribution. These essential tools empower administrators to effectively monitor platform health, understand user behavior, and make informed decisions for the growth and maintenance of the Medigeek community.

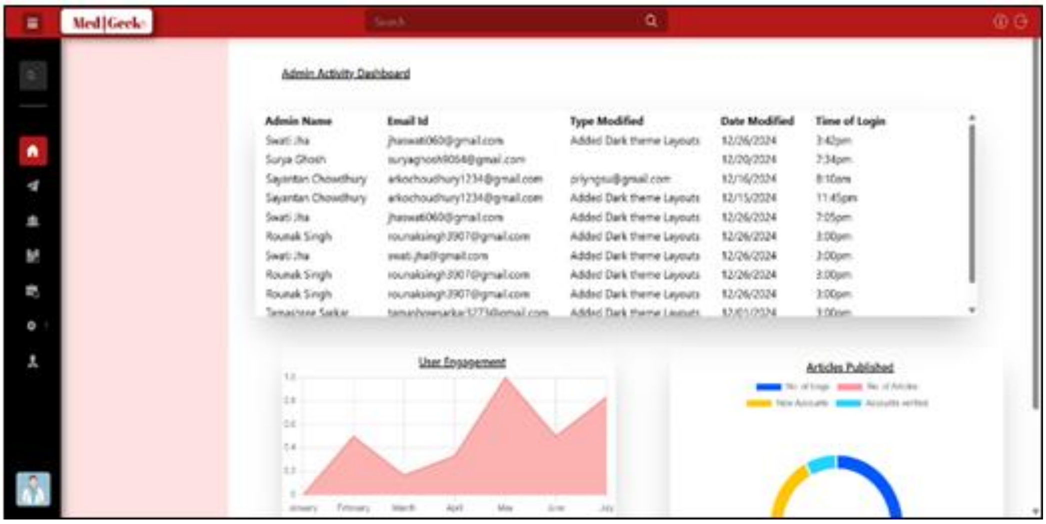

Fig 3.8: Visuals of the Admin Dashboard.

IV. CONCLUSION

MediGeek transcends the typical social platform, establishing itself as a dedicated ecosystem meticulously crafted to address the **Error! Reference source not found.Error! Reference source not found.**dynamic de mands of the medical community. In today's environment where seamless collaboration, swift information dissemination, and robust professional support are paramount, MediGeek offers a unified digital space for doctors, healthcare professionals, and aspiring medical students to flourish collectively.

The platform fosters focused communication through department-specific channels, enabling in-depth discussions among peers within specialized fields. Its integrated blogging functionality empowers users to share valuable insights, firsthand clinical experiences, and cutting-edge research findings, thereby cultivating a vibrant culture of knowledge exchange and continuous learning. Furthermore, MediGeek strategically bridges the gap for medical students, providing invaluable opportunities to connect with seasoned professionals, seek crucial mentorship, and gain early exposure to diverse medical specialties, shaping their career trajectories.

By seamlessly integrating networking opportunities, educational resources, and collaborative tools, MediGeek empowers users at every stage of their medical journey, from novice students to experienced practitioners. It serves as a contemporary solution to the **Error! Reference source not found.**challenges of p rofessional isolation, making meaningful connections more accessible and significantly more impactful, fostering a stronger and more interconnected medical community. With MediGeek, the medical world gains a trusted and dynamic space to collectively grow, inspire innovation, and lead the way in healthcare advancements.

V. ACKNOWLEDGEMENT

We would like to express our sincere gratitude to the entire team behind MediGeek for their vision and dedication in creating this innovative platform for the medical community. We also extend our deepest appreciation to our mentor, **Dr. Soumitra Roy**, for their invaluable guidance and support throughout this project, whose insights have been instrumental in our understanding of MediGeek's significance.

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Zerosphere: Simplifying Financial Management

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ABSTRACT

Managing money is an essential skill in today's fast-moving digital world. To make this easier, we created ZeroSphere, a simple and effective expense tracker. ZeroSphere is a web app that offers a smooth and user-friendly experience. Users can log transactions, categorize expenses, and set budget limits with ease. The app helps users understand their spending habits through clear charts and reports, encouraging smarter financial choices. Features like custom categories and budget alerts support better money management and goal tracking. ZeroSphere focuses on being simple, secure, and accessible. Unlike other complex or expensive apps, it keeps things easy and respects user privacy. With a strong backend and a responsive frontend, ZeroSphere's main goal is to help people feel in control of their finances. In the future, it may include features like predictive budgeting and automatic transaction tracking. ZeroSphere aims to make managing money easy, safe, and affordable for everyone.

Keywords — web application; expenditure; zero trust; track expense; OCR

I. INTRODUCTION

In today's fast-paced digital world, personal finance management has become increasingly crucial. Individuals and businesses alike rely on various tools and applications to track their expenses, create budgets, and make informed financial decisions. Expense tracking applications have gained significant popularity, offering users convenient ways to monitor their spending habits, identify areas for savings, and achieve their financial goals. These applications typically provide features such as expense categorization, budgeting tools, and financial reports, empowering users to take control of their finances. However, traditional expense tracking applications often rely on perimeter-based security models, which assume that anything within the network is trusted. This approach has significant limitations in today's evolving threat landscape. With the rise of remote work, cloud computing, and the increasing sophistication of cyberattacks, perimeter-based security is no longer sufficient to protect sensitive financial data.

This project aims to address these limitations by developing a secure and User-friendly expense tracking application based on a Zero Trust security architecture. Zero Trust[1] is a security paradigm that assumes no devices or users are inherently trustworthy[2], regardless of their location within or outside the organization's network. By adopting a Zero Trust approach[3], we can enhance the security and privacy of user financial data[4], mitigate the risk of data breaches, and provide a more secure[5] environment for managing personal finances.

II. RELATED WORKS

Numerous financial tracking tools exist today[6], including Mint, You Need a Budget (YNAB), and spreadsheet-based trackers[7]. These platforms have succeeded in simplifying financial tracking but often fall short in securing user data comprehensively. Mint, for example, offers features such as automatic transaction categorization and goal setting, but includes advertisements and provides limited control over data privacy. YNAB focuses heavily on budgeting and long-term planning[7] but is a paid service and does not implement advanced data protection frameworks.

Meanwhile, recent research has emphasized the importance of Zero Trust Architecture in modern software systems[6]. This model incorporates key principles like continuous authentication, the least privilege access, micro-segmentation, and end-to-end encryption. When applied to financial applications, these measures can prevent unauthorized access and limit the impact of breaches[8]. The field is also seeing a rise in the use of machine learning for fraud detection, anomaly identification, and personalized financial recommendations[8]. Together, these advancements highlight the need for applications that not only offer smart budgeting tools but also incorporate proactive security mechanisms.

III. PROPOSED SYSTEM

ZeroSphere is a privacy-focused, web-based personal finance application designed to help users efficiently track their income and expenses in a secure environment. Developed using the MERN stack—MongoDB, Express.js, React.js, and Node.js — the system is both scalable[9] and responsive, offering a seamless user experience with robust backend functionality.

The front end of ZeroSphere, built with React.js, features an intuitive and minimalist dashboard where users can manually input financial transactions. Users can filter their records by date, category, or payment method, making it easy to review and analyze past spending. The user interface prioritizes clarity and accessibility, catering to individuals with limited technical experience while still offering powerful functionality.

The back end, powered by Node.js and Express.js, manages all core logic, including user authentication, transaction handling, data validation, and session control. MongoDB serves as the primary data store, housing user profiles and financial records. All sensitive data is encrypted, and passwords are securely hashed using SHA-256 to ensure the highest level of data protection.

What distinguishes ZeroSphere from conventional expense trackers is its adoption of the Zero Trust security model[8]. This model operates on the principle that no user, device, or session is inherently trustworthy[9]. Every access request is validated through layered Identity and Access Management (IAM) protocols[6]. Features such as session monitoring, role-based access control[8], and multi-level encryption are incorporated to safeguard data integrity and user privacy. Unlike many financial tools that prioritize design over security, ZeroSphere offers a holistic solution that excels in both usability and protection.

3.1 Key Functional Features

3.1.1 User Authentication

This feature allows users to sign up and log in seamlessly via Google or using an email and password. It also includes an anonymous mode, enabling users to operate the app locally without creating an account [Fig.3].

3.1.2 Manual Expense&Income Tracking

Users can manually record transactions by entering key details like the amount, date, description, and category. Income and expenses are tracked separately, offering clarity. The feature also supports budget limits for specific categories and provides notifications to help users stay on top of their financial goals.

3.1.3 Custom Categories&Tagging

Users can create custom categories, such as Groceries, Utilities, or Travel, based on their preferences [Fig.1]. Additionally, tags allow for streamlined organization and filtering, with examples like #Work, #Family, or #Vacation for better financial management.

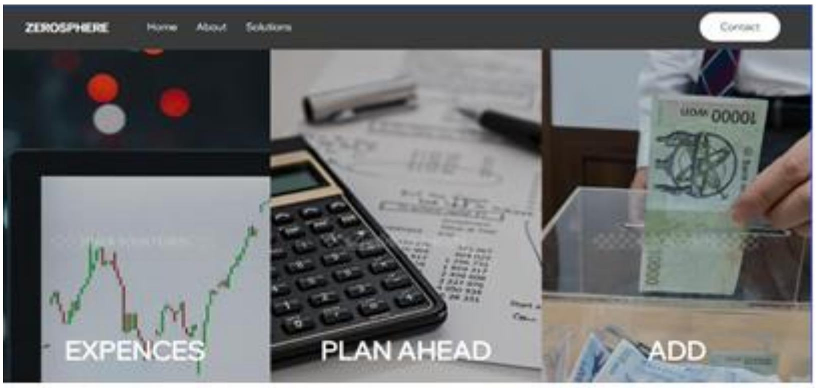
3.1.4 Visual Analytics Dashboard

A variety of dynamic charts and graphs, including pie charts, bar graphs, and line charts[9], provide a comprehensive and easy-to-understand view of financial data. Daily, monthly, and category-specific summaries are available, along with tools to analyze spending trends over different time frames [Fig.2].

3.1.5 Data Sync

To ensure data accessibility across devices, this feature offers optional cloud synchronization via Firebase or MongoDB Atlas.

ZeroSphere offers a thoughtful balance between user autonomy and technological intelligence. Its manual input approach, reinforced by strong security and visual insight tools, makes it an ideal solution for users who prioritize privacy, customization, and control over automation. With a solid foundation in place, the system is designed to evolve, incorporating smarter features and expanding its utility in the future.



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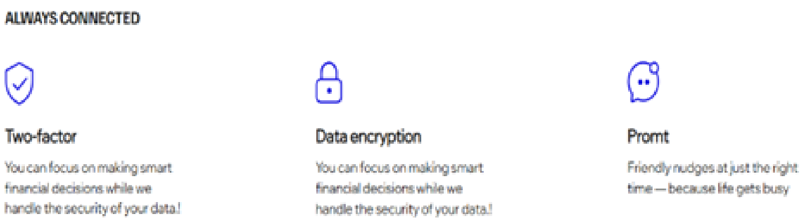
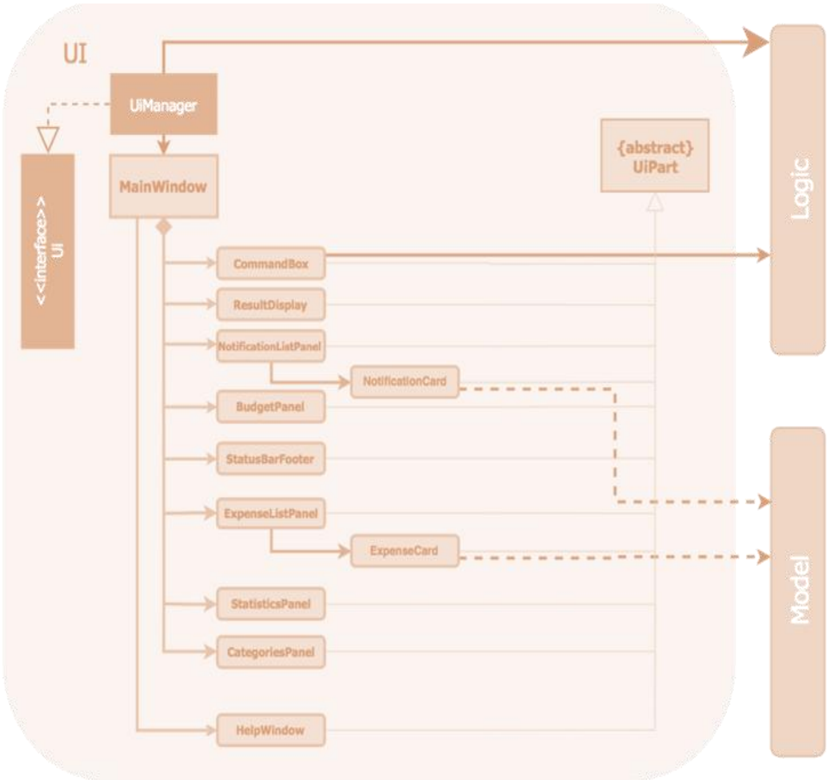


Fig:3

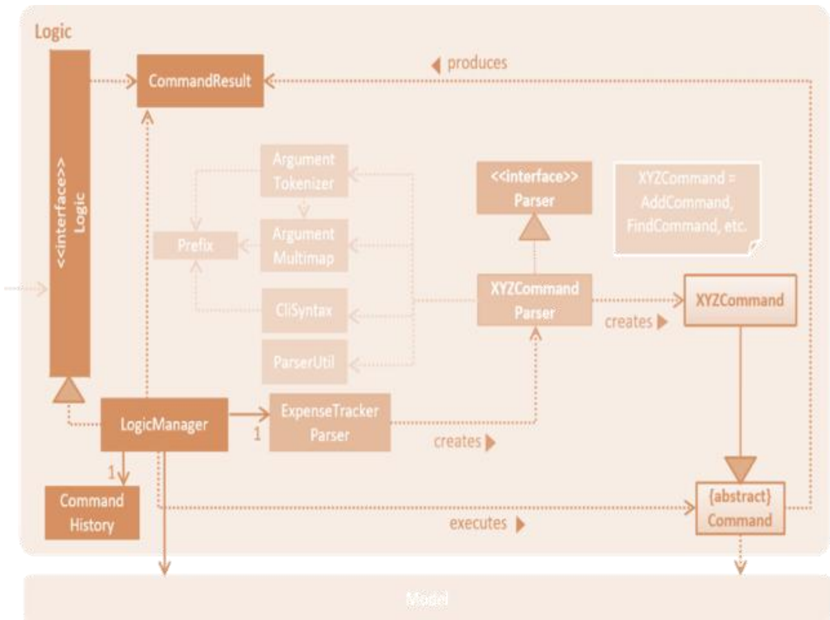
IV. ARCHITECTURE AND DESIGN

The architecture of ZeroSphere follows an event-driven, modular design, which separates concerns into different functional components. These include the User Interface (UI), Logic, Model, and Storage layers.

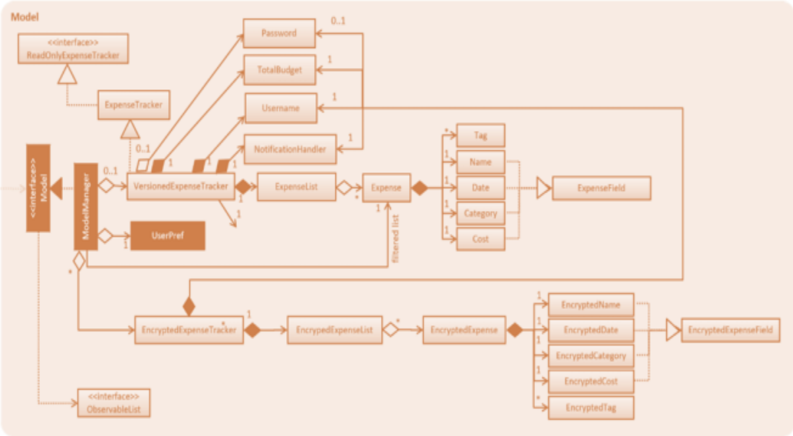
4.1. The user interface is built using React.js, featuring components like transaction input forms, analytics dashboards, and alert modals. All interactions in the UI are event-triggered and are dynamically linked to the application's state, ensuring real-time updates without page reloads.



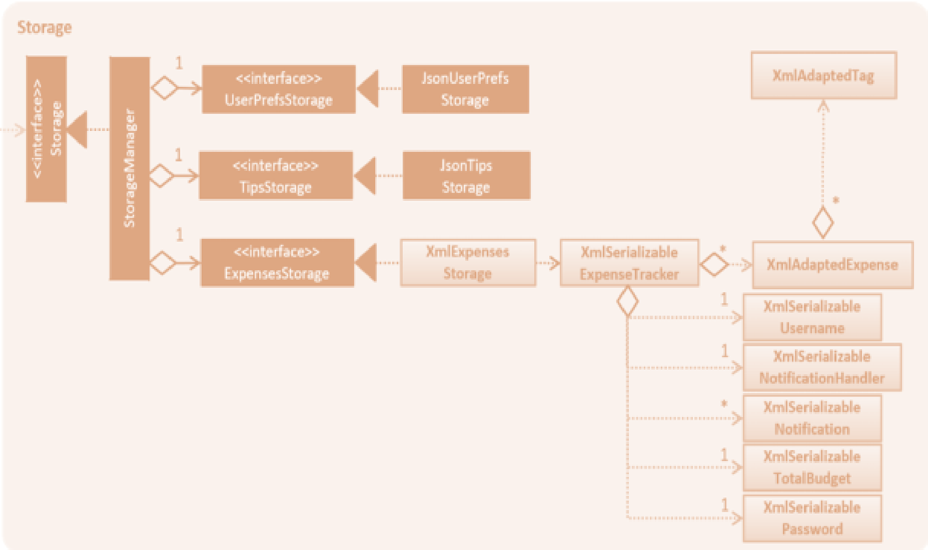
4.2. The logic component acts as the bridge between user actions and backend operations. User inputs are parsed and interpreted as commands, which are then executed to perform actions such as adding a transaction or generating a report. Each command returns a result object that updates the UI with appropriate messages or graphical feedback.



4.3. The model layer handles all in-memory data and syncs it with the database as needed. It maintains lists of categorized expenses and user preferences and ensures that no direct manipulation is possible from outside components, thereby protecting data consistency.



4.4. The storage system manages all read/write operations. Transactional data is stored in MongoDB and accessed through encrypted APIs. User preferences and authentication credentials are stored as JSON objects, while sensitive data is encrypted during both transit and storage.



V. COMPARATIVE ANALYSIS

To assess the effectiveness of ZeroSphere, we compared it with two popular tools—Mint and YNAB—across several dimensions. In terms of cost, Mint is free but includes advertisements and offers limited customization. YNAB, while comprehensive, is a paid tool[2]. ZeroSphere, in contrast, is completely free and open source, with no ads or data monetization. When evaluating customizability, both ZeroSphere and YNAB allow extensive user control over categories, limits, and interface preferences[2]. Mint offers moderate flexibility. In terms of simplicity, ZeroSphere's clean interface and guided onboarding make it highly approachable, especially for first-time users. The security dimension is where ZeroSphere truly excels. Both Mint and YNAB implement basic data encryption and login security[2], but neither uses Zero Trust principles. ZeroSphere includes multifactor authentication, session verification, micro-segmentation, and secure APIs to protect against unauthorized access and data leakage.

5.1. Comparison with Existing Solutions

Feature	Mint	YNAB	Proposed Tracker
Cost	Free (Ads)	Paid	Free (no Ads)
User Customization	Limited	High	High
Simplicity	Moderate	Moderate	High
Data Privacy	Limited	Limited	High

5.2. Project Strengths for Evaluation

Aspect	Strength
Innovation	Focus on privacy and user control—no SMS or bank scraping
Real-world Use	Appeals to everyday users, especially in cash-heavy or privacy-focused areas
Learning Outcome	Covers full stack, authentication, database design, UX, and data viz
Expandability	Easy to add bank/API support later if desired
Presentation Value	Beautiful dashboards and real-time insights make it demo-friendly

VI. CONCLUSION AND FUTURE SCOPE

ZeroSphere presents a forward-thinking solution to a fundamental challenge in personal finance: how to track expenses securely, efficiently, and privately. By adopting a privacy-first design and eliminating the need for SMS permissions or sensitive bank credentials, it empowers users to manage their finances on their own terms — without compromising data security.

This approach not only aligns with modern digital privacy concerns but also opens the door to a broader user base. From students and freelancers to individuals in cash-based economies, ZeroSphere serves those who value manual control, simplicity, and trust over automation that demands unnecessary access.

What sets ZeroSphere apart is its fusion of usability and robust security — anchored in the Zero Trust model. It offers a streamlined, intuitive experience without sacrificing privacy, making it a compelling choice in an age where financial data is increasingly vulnerable.

Looking ahead, ZeroSphere holds strong potential for growth and innovation. The system incorporates secure banking APIs to enable optional automated transaction imports, streamlining financial management for users. It also leverages AI-powered spending insights and predictive budgeting tools to assist users in making more informed financial decisions. Multi-language support has been included to ensure wider accessibility and inclusivity, catering to a diverse user base. Additionally, blockchain-based transaction logs enhance transparency and auditability, providing users with a secure and trustworthy way to manage their financial data.

Additionally, current limitations — such as OCR performance in low-light conditions or difficulty identifying key receipt regions — present opportunities for further research and technical refinement. Addressing these challenges could significantly improve user experience and expand the app's use cases.

In conclusion, ZeroSphere is more than just an expense tracker — it's a privacy-respecting, user-empowering platform designed for the evolving landscape of personal finance. With continued development and user-focused innovation, it has the potential to set a new standard for secure, intelligent, and accessible financial management tools.

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Feedforward Neural Network in MATLAB for One Dimensional Linear Convection Equation

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ABSTRACT

In this research, a feedforward neural network in MATLAB is used to solve a one-dimensional linear convection equation, and its performance is compared to an analytical solution. By learning geographical and temporal patterns from data produced by the explicit first order upwind technique, we employ an ANN to approximate the temperature distribution. In MATLAB, the Levenberg-Marquardt algorithm is utilized as an optimization method. In order to illustrate the numerical solution of the convection equation and error function, surface and contour maps are also created. Additionally, a quantitative analysis of the prediction is conducted by comparing the precise answer with the predicted real values using the Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and R2 value. When compared to traditional numerical techniques, the results show that the ANN is an accurate and effective substitute for solving linear PDEs.

Keywords: Artificial Neural Network, Convection Equation, Machine Learning, Upwind Scheme, Mathematical Modeling

I. INTRODUCTION

One dimensional linear convection equation is a fundamental PDE that models the distribution of quantity without diffusion in a given zone over time. It is extensively used across various fields, including thermodynamics, fluid mechanics. Traditionally, numerical methods [1-6, 12, 15, 17, 21-22] such as FDM, FVM, BVM and FEM are employed to solve the convection equation. While these methods are effective, they often require fine-tuning of parameters and can be computationally expensive, particularly for complex domains or long time simulations.

Utilizing the aforementioned trending numerical and machine learning methods, a few papers have introduced the coupling of machine learning and artificial neural networks (ANN) [1-4, 9, 13, 18, 19, 23] with conventional methods to solve partial differential equations (PDEs), particularly related to convection–diffusion. Salman et al. [7] develop a deep learning-based solver, which demonstrates good approximation to the solution of the advection–diffusion equation and demonstrates it against finite difference methods. Seo [8] makes a contribution by developing a novel pre-training domain decomposition approach that uses ANNs contains applications for solving more general elliptic boundary value problems. Reddy et al. [11] used in basically ANN based models based on ANNs to treat the nonlinear magneto-convection behaviour of a sample tilted porous layer with respect to sheath. These enhance the ability of the ANN to treat more complex multiphysics problems. Thander and Bhowmik [10] used an ANN version that incorporated the Levenberg–Marquardt algorithm of the standard 2D Poisson equation in the relational learning approach to obtain a numerical solution. Kumar et al. [14] introduced explored ANN as a method of data reduction in a conjugate heat transfer problem through experimental and CFD based inverse approaches. Sahoo and Gupta [16] developed a higher-order finite difference method scheme for convection–diffusion problems that are time-dependant, stating that it provides mathematically satisfying results with some expected variations in numerical performance across a range of parameter values. Finally, Varun Kumar et al. [20] used ANN to create modeling system that predicted the transient thermal analysis of stretching/shrinking fins. These clearly support neural networks as valuable in thermal system simulations. Overall, these articles show ANNs can potentially develop solutions to PDEs in scientific and engineering applications in a variety of ways.

Here we explore use of a feedforward neural network to solve one-dimensional linear convection equation and compare its predictions with the exact analytical solution. The implementation of the network is examined using key metrics such as Mean Absolute Error, Root Mean Square Error and R-squared (R^2). This approach illustrates the uses of machine learning for solving partial differential equations, now providing alternate pathways that are more promising with shorter run times than traditional numerical methods.

The structure of the paper follows: Section II provides discuss the linear convection equation and the grid mesh generation. Section III gives compact details of the feedforward neural network in MATLAB. Section IV shows the numerical results. Section V is for concluding remarks.

Section VI is future directions for the research.

II. One Dimensional Convection Equation

One dimensional linear convection equation[24-25] within rectangular solution zone where $t \in [0, P]$ and $x \in [0, Q]$ is $\dfrac{\partial v}{\partial t} + c\dfrac{\partial v}{\partial x} = 0$ (1)

Here $v(x,t)$ is the quantity being transported position at (x,t). c is the convection constant.

We prescribe Dirichlet Boundary Conditions as,

$$v(0,t) = 0, \ \forall t \in (0, P)$$

and no explicit right boundary condition is applied here as first-order upwind scheme, with positive wave speed c>0, information flows from left to right, so no boundary condition is needed at the right edge. Here the initial condition is

$$v(x,0) = \sin \pi x, \ \forall x \in (0, Q)$$

To find numerical solution of (1), we have discretised the domain into grid points [11,13]. Here Δx and Δt are grid size along x and t directions respectively. Let (x_i, t^n) be a grid point in the zone. Then $x_i = x_0 + i\Delta x, t^n = t^0 + n\Delta t$. We have considered $\left(x_0, t^0\right)$ as (0,0). P=0.6, Q=1, $\Delta x = 0.02, \Delta t = 0.02$

Approximate solution of this linear convection equation can be obtained using the following explicit **first order upwind** scheme

$$v_i^{n+1} = v_i^n - c\frac{\Delta t}{\Delta x}\left[v_i^n - v_{i-1}^n\right] \qquad (2)$$

This is first order scheme for both space and time.

Here Courant–Friedrichs–Lewy (CFL)

condition is $\left|c\frac{\Delta t}{\Delta x}\right| \leq 1$.

Analytical solution of above convection equation mentioned in Eq. (1) is

$v_E = \sin \pi (x - ct)$.

The error function($\|v_E - v_{ANM}\|_2$) is computed in L_2 space [15, 17]. Here v_{ANM} is the ANM solution of Eq. (1).

III. Neural Network in MATLAB

ANN uses a data-driven approach for solving differential equations, such as the one-dimensional convection equation. In this study, we trained the ANN using numerical data generated from the explicit Finite Difference Method (FDM) for the convection equation over a spatial domain of Q=1 with 50 grid points, and a temporal domain of P=0.6 with 30 grid points. The numerical solution uses a convection constant c=1 and a time step size created by CFL condition to assure the solution is stable. The ANN is feedforward with two hidden layers with 25 neurons and *tansig* activation functions and a *purelin* activation function for the output layer. The ANN is trained using the Bayesian Regularization (*trainbr*) algorithm, with a total of 1000 epochs and a performance goal of error 10^{-6}, which achieves a reasonable balance between accuracy and generalization. The ANN learned to approximate the temperature distribution by mapping its input spatial and temporal coordinates to the temperature value stored in the upwind scheme. With the ANN model well trained, it was able to provide a continuous approximation to the solution of the convection equation, thus providing a cost and time-saving advantage in computing time and the ability to interpolate outside of the discrete grid points from the upwind scheme. Finally, the performance of the ANN solution is verified with statistical metrics of MSE, MAE, and R^2, and visual site inspections of surface plots and contour maps with the original numerical and exact solutions.

IV. Design and Training of ANN in MATLAB

To reduce the difference between output and target results, training ANN requires adjustment of weights and biases from input data. An extensive review of neural networks can be found in [1-4, 18-19, 23]. The Backpropagation algorithm used by Multi-layer ANN for applying successive weight and bias updates during training. Precision levels for an ANN depend on accessing sufficient amounts of training data to work with.

The training dataset splits regularly into three different groups that are training data validation data and testing data. The three divisions evaluate the effectiveness of the training individually. The assessment method gives cumulative results for the whole data set and helps researchers in comparing different training methodologies and configurations of ANN.

The MATLAB environment enables us to generate a huge 1500X150 sample dataset for solving convection equation. In the training phase, three different sets of samples aggregating 150X150 are used where seventy percent is utilized for training and fifteen percent each for validation and testing respectively. The ANN is trained using the Levenberg-Marquardt algorithm which was executed to perform three training iterations for every network architecture that comprised 1000 epochs [10, 14]. Here Courant-Friedrichs-Lewy (CFL) [24-25] value equals 0.50.

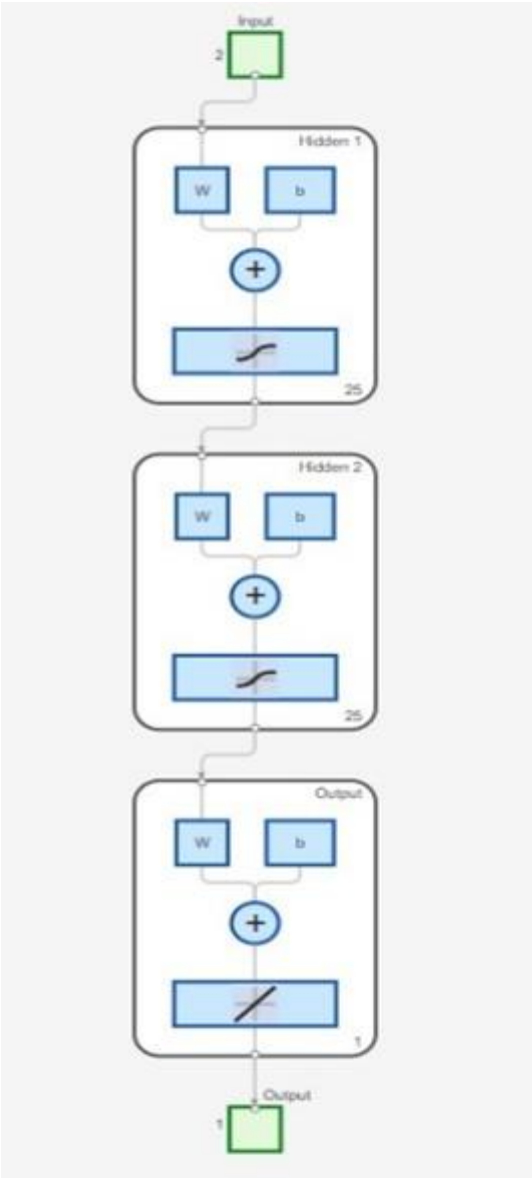

Figure 1: ANN consisting of two hidden layers, each containing 25 neurons

The ANN architecture developed for solving the convection problem in problem (1) is shown in Figure 1. The surface and contour plots, respectively, in Figures 2 and 3 illustrate computational solution for the convection equation using current approach.

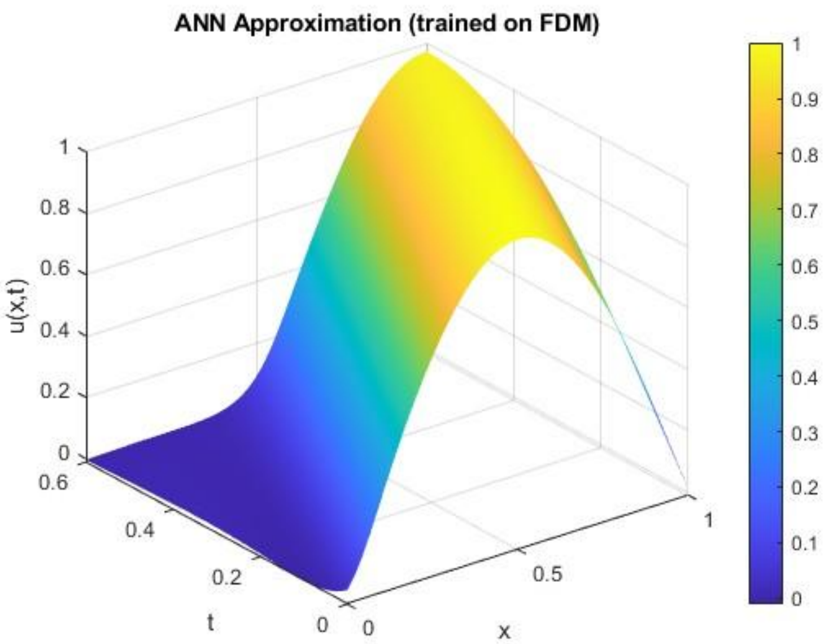

Figure 2: 3D visualization of convection equation solution

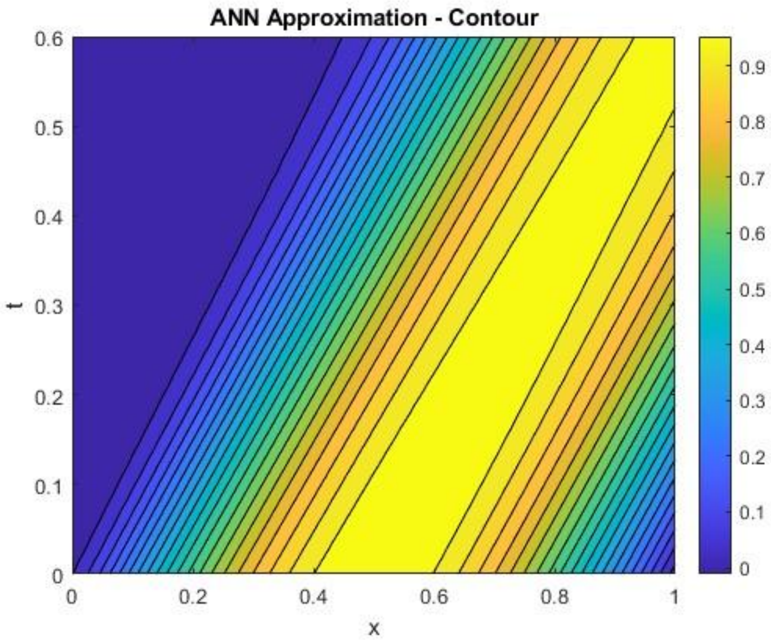

Figure 3: Contour visualization of convection equation solution

The results of training the Levenberg-Marquardt algorithm (LMA) are presented in Figures 4 through 7. The performance curve in Figure 4 shows that as the epoch number rises, MSE lowers. The test set error and validation set error exhibit same type of patterns, which is notable. This ANN model does not show any significant overfitting problem up to epoch 1000. The MSE drops to an exceptionally low value of 7.7152e-06 at epoch 16. The gradient plot in Figure 5 provides information about the optimization methods used to achieve global solutions.

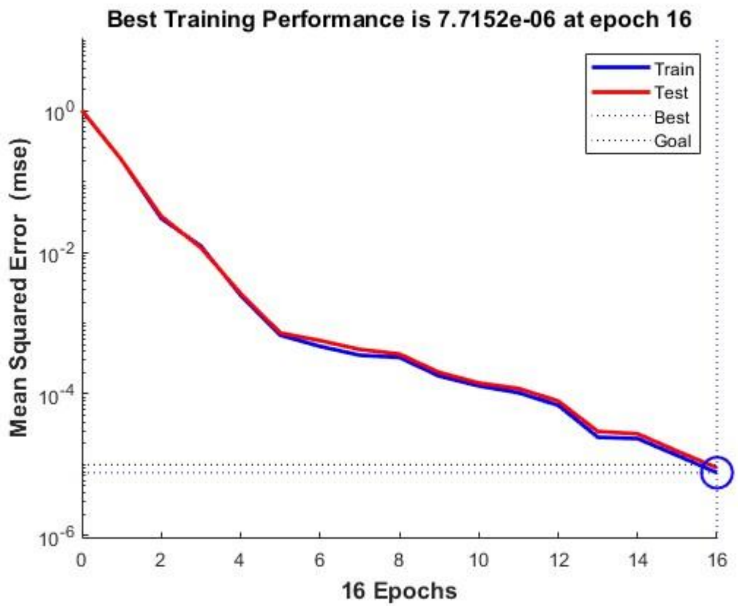

Figure 4: MSE Values Across Various Training Epochs During Optimization.

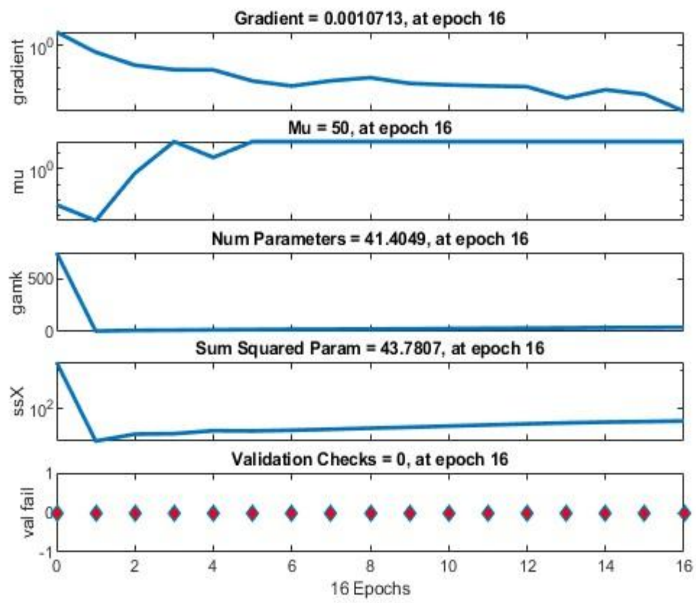

Figure 5: Training State of the Neural Network Observed at Various Epochs During the Learning Process

Table 1: Statistical Performance Metrics after epoch 16

Metrics	Values
MSE	0.0001459
MAE	0.0082954
R^2	0.9978976

A detailed overview of the ANN's performance is provided in Table 1. It is realistic to assume that the ANN estimates the upwind scheme solution with little variance because the MSE and MAE values are low. The ANN is accurately modeling the dynamics of the convection problem using the parameters provided, as evidenced by the fact that the R^2 is closest to 1, indicating a very good correlation. The accuracy and validity of any ANN-based method are confirmed by all of this evidence.

In Figure 6, ANN model error histogram is partitioned into 20 bins. The yellow line in the figure indicates zero error, and we can see there are 920 instances of these zero error during the training period. Figure 7 now shows the relationship between expected output values and measured target values presented separately for training and testing steps. The R values shown in each of the three sub-figures indicate the ANN model creates a positive outcome. It is also worth noting that Figure 7, with slope and intercept values that are approximately equal to 1.0 and 0.0, respectively, for all examples, demonstrates an excellent match. Finally, as Figure 7 shows for all cases, the R-value was continually about 100%, demonstrating excellent performance for all data.

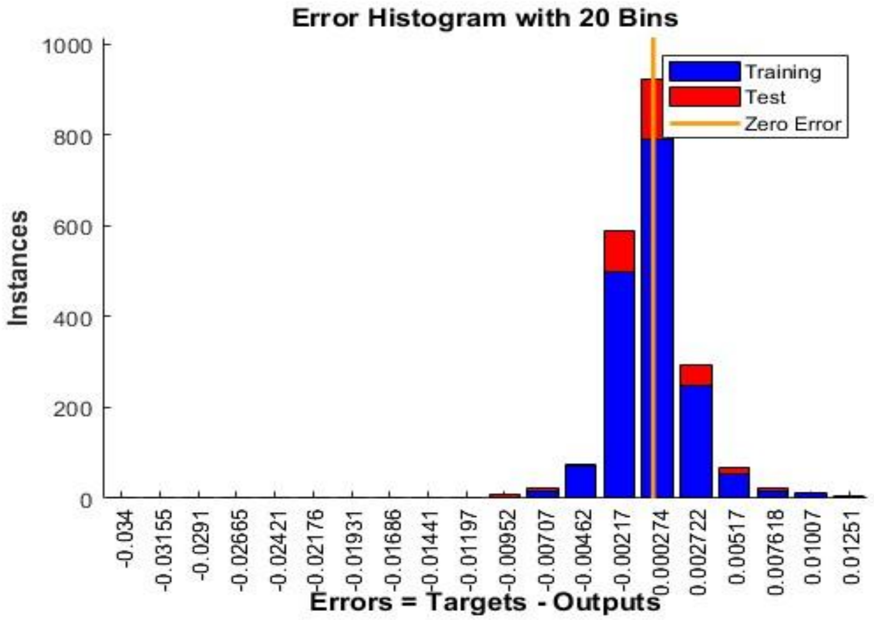

Figure 6: Histogram of Neural Network Training Errors Using 20 Bins to Illustrate Error Distribution

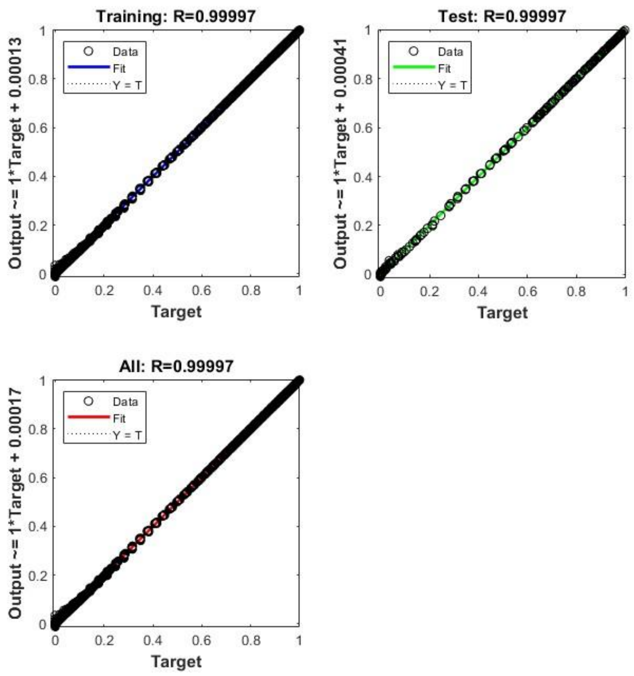

Figure 7: Regression Analysis of Neural Network Training Results Showing the Relationship Between Predicted and Actual Values

Plotting the difference the analytical and computed solutions indicates an error will be in some order 10^{-8}.

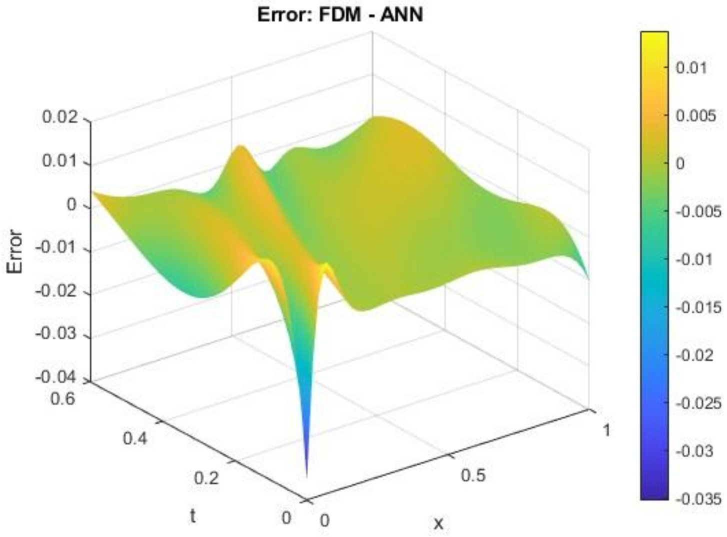

Figure 8: 3D surface plot depicting the error function

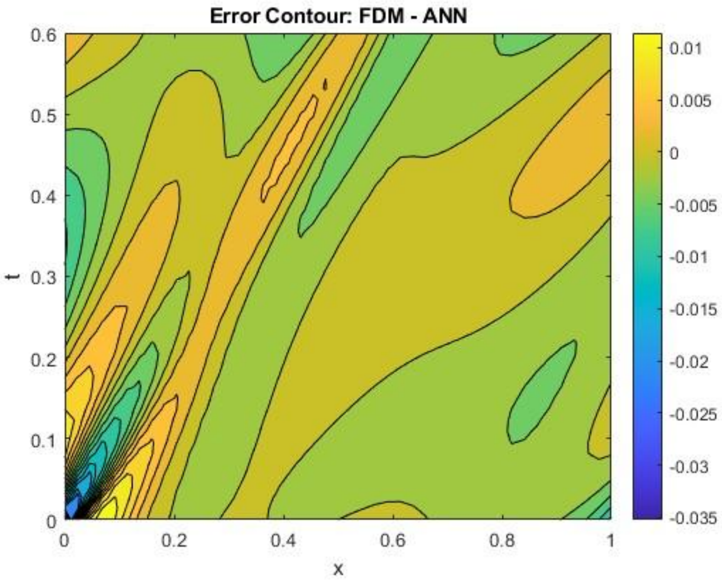

Figure 9: Contour map illustrating the error function

3D and 2D plots of function of error for single dimensional linear convection equation are shown in Figures 8 and 9. This error function for L_2 space is found by comparing the numerical solution produced by present method and the convection equation's known analytical solution.

Liu et al. [23] used a similar strategy. The presented method using an ANN (artificial neural network) enabled a radial basis function collocation method to calculate a computational solution for PDEs. In their method, where they saw maximum and minimum distances radially from their boundary points of their solution domain and the external fictional sources, they used the specified value at the boundary for the dependent variable in their training data. The method works perfectly with Dirichlet boundary conditions. Our method has a failure in its practice in that the exploration of the solution domain must be discretized. Liu et al. [23] do not need this from their consideration. We also have a limitation, that our method can also not use linear PDEs with complicated geometries where one could not use uniform grids with various ratios and sizes.

V. CONCLUSION

In this research, an ANN was successfully trained to establish a solution of one-dimensional linear convection equation using numerical data generated according to an upwind scheme. A two-hidden layer ANN with 25 neurons presented the capability to learn complex spatial and temporal relationships hidden within the dataset. The specific trained model provides a continuous and computationally efficient approximated solution of the convection equation that circumvents the need for discrete numerical methods. The performance of the ANN was statistically analyzed with MSE, MAE, and R^2 providing strong correlation of performance between the ANN and numerical finite difference solution. Visual comparisons such as surface plots and contour plots provided an additional demonstration of the accuracy of the ANN model. The ANN-based approach acknowledged its computational efficiency and flexibility in dealing with complex datasets, however, accuracy could be improvised when considering optimization of network architecture, the resolution of training data, or the use of physics-informed learning. All in all, it is concluded that neural networks can serve as a reasonable alternative to conventional numerical schemes for solving one dimensional linear convection problems understandably through following future modifications.

VI. FUTURE PLAN

In future, our research will focus on accuracy and utilization of higher quality training data. The work will further extend the 2D convection-diffusion equations to make the model more realistic and applicable in practical situations. Further, an attempt will be made to integrate ANNs with Physics-Informed Neural Networks (PINNs) so that learning processes take place under proper physical constraints. This new technique will also be tested against other state-of-the-art numerical techniques, such as the Lax-Wendroff scheme, for efficiency evaluation.

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Hand Gesture Recognition in Low Light Conditions

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ABSTRACT

This project addressed the challenge of hand gesture recognition in low-light conditions, where traditional systems often fail due to poor visibility and degraded image quality. We developed a gesture recognition model capable of detecting three specific gestures—palm open, swipe right, and thumbs up—under varying illumination levels. The system utilized image enhancement techniques, region of interest (RoI) segmentation, and a Convolutional Neural Network (CNN) for accurate gesture classification. We trained the model on a custom dataset that included diverse lighting scenarios and evaluated its performance by tracking accuracy and loss over multiple training epochs. The model showed consistent improvements in recognition accuracy and convergence behaviour, indicating effective learning and robustness against lighting variations. Although the system was limited to a small set of gestures, it demonstrated reliable performance in controlled low-light environments. This work contributes to the ongoing development of accessible and adaptive gesture-based interfaces, with potential for future expansion to more complex gesture sets and broader real-world use cases.

Keywords: Hand Gesture Recognition, Low Light Conditions, Human-Computer Interaction, Image Processing, CNN, Gesture Classification

I. INTRODUCTION

Hand gesture recognition has rapidly evolved as a key technology in human-computer interaction (HCI), providing an intuitive and natural means for users to communicate with machines. Its significance spans across a wide range of domains, including virtual and augmented reality (VR/AR), healthcare, smart homes, robotics, and automotive interfaces. By enabling contactless interaction, gesture recognition systems offer both convenience and hygienic operation, particularly in environments where traditional input devices such as keyboards and touch screens are impractical or unsanitary.

Despite its growing applications, one of the fundamental challenges faced by current gesture recognition systems is their poor performance under low-light conditions. Most existing models rely heavily on visible light imaging, which can result in degraded image quality, loss of hand features, and increased background noise in dim environments. These factors collectively impair the system's ability to detect, interpret, and classify hand gestures accurately. In real-world applications—such as night-time driver assistance, healthcare monitoring in dim rooms, or gaming in controlled lighting—this limitation significantly restricts usability and reliability.

To bridge this gap, our project aims to develop a robust hand gesture recognition system that performs reliably in low-light scenarios. The system is built on a modular pipeline incorporating (a) image enhancement to improve visibility, (b) region of interest (RoI) segmentation to isolate the hand from the background, (c) finger identification, and (d) gesture classification using a deep learning model. We restrict the model to classify three specific gestures—palm open, thumbs up, and swipe right—chosen for their relevance in interactive applications.

The core of our system is a custom-designed Convolutional Neural Network (CNN) trained on a diverse dataset that includes augmented images representing different lighting conditions, hand orientations, and backgrounds. Data was collected and pre-processed using libraries such as OpenCV and Media Pipe, with advanced augmentation techniques applied to ensure model generalization and resilience. The system's performance is evaluated based on accuracy, loss, and inference speed, with promising results across these metrics.

The primary objectives of this paper are:

- To design a gesture recognition system optimized for low-light environments.
- To build a clean and balanced dataset for model training.
- To ensure real-time classification through efficient model deployment.

Our contributions include the creation of a dedicated low-light hand gesture dataset, the development of a lightweight yet effective CNN model, and the implementation of a real-time recognition interface using Python and OpenCV.

II. LITERATURE REVIEW

Gesture recognition has become a vital aspect of human-computer interaction (HCI), offering contactless, intuitive, and accessible means of communication between users and machines. A systematic review of recent literature reveals a wide range of innovative approaches, tools, and applications aimed at improving the accuracy, responsiveness, and robustness of hand gesture recognition systems.

Table 1, evaluates various systems based on tools used, performance metrics, and practical challenges encountered.

Paper	Core Concept	Tools Used	Performance	Strengths	Limitations
[1] A.F.Ramadan et al. (2024)	Vision-based real-time laptop control	OpenCV, MediaPipe	85%	Contactless, accessible, customizable	Environmental sensitivity, fatigue, hardware limits
[2] Tiwari et al. (2023)	Gesture-based volume controller	OpenCV, PyCaw, MediaPipe	90–95%	Real-time feedback, flexible	Sensitive to lighting, gesture standardization issues

Paper	Core Concept	Tools Used	Performance	Strengths	Limitations
[3] Munir Oudah et al. (2020)	Review of vision and sensor-based methods	CNNs, IMUs, EMG	77.2–98.5%	Non-invasive, privacy-friendly	Sensor noise, power consumption
[4] D.D.Meshram et al. (2024)	Virtual mouse via fingertip detection	MediaPipe, TensorFlow	90–96%	Intuitive, safe, cost-effective	Fatigue, limited low-light adaptation
[5] A.Ismail et al. (2021)	Haar-cascade-based recognition	OpenCV	80–90%	Lightweight, fast, customizable	Poor lighting robustness, lacks GUI
[6] F.Sarani et al. (2021)	Virtual blackboard with HSV + HMM	OpenCV, 3D CNN	90–97%	Real-time, versatile	Complex hardware, latency issues
[7] Rayane Tchantchane et al. (2023)	Wearable sensor-based recognition	IMU, sEMG	70–98%	High accuracy, real-time	Costly, user discomfort, privacy issues
[8] Jing Qi et al. (2024)	Depth-camera-based gesture recognition	Depth camera, SVM, GMM	70–98%	Effective for HRI, scalable	High computation, limited monocular camera use

Table 1: Comparative Summary of Existing Gesture Recognition Systems

While numerous approaches have demonstrated real-time gesture recognition with decent accuracy, most face significant limitations under varying environmental conditions—particularly low-light scenarios. Additionally, many methods rely on specialized hardware (e.g., depth sensors or wearables), which may not be feasible for general use. Systems utilizing conventional RGB cameras often lack robustness when lighting conditions deteriorate. Furthermore, gesture standardization and scalability across diverse users remain unresolved issues.

Our work addresses these limitations by proposing a lightweight, camera-based hand gesture recognition system optimized for low-light environments using a custom CNN. It avoids reliance on depth sensors or wearables, aiming for broader usability and affordability. Moreover, the system focuses on three clearly defined and commonly used gestures, enhancing reliability and reducing classification ambiguity.

III. PROPOSED METHOD

This section outlines the systematic approach adopted for the development and implementation of a real-time hand gesture recognition system. The methodology comprises dataset preparation, model architecture, training strategy, and real-time deployment, each detailed to ensure reproducibility.

Dataset Construction: To train an effective gesture recognition model, a custom dataset was constructed comprising four distinct hand gesture classes: *thumbs up*, *palm open*, *swipe right*, and *no gesture*. Images were captured using a standard webcam in real-time, facilitated by the OpenCV and Media Pipe libraries for robust hand tracking and Region of Interest (ROI) extraction. Each frame was converted to RGB format for compatibility with the Media Pipe hand landmark detector. Bounding boxes were dynamically calculated around detected hand landmarks and slightly expanded to ensure complete gesture capture. These cropped hand images were then stored in a structured directory, with folders labeled according to gesture class.

To enhance model generalization, data augmentation techniques were applied, including rotation, horizontal flipping, brightness modulation, and zooming. Each class comprised approximately 500 original images, which, after augmentation, formed a balanced and diverse dataset.

Data Pre-processing: All images were resized to 64×64 pixels and normalized to ensure uniform input to the neural network. The dataset was subsequently serialized into NumPy arrays (x.npy, y.npy) for optimized I/O during training. Label encoding was used to convert class labels into numerical form suitable for classification tasks.

Model Architecture: A custom Convolutional Neural Network (CNN) was developed to classify hand gestures. The architecture consists of:

- Input Layer: Accepts 64×64×3 RGB images.
- Convolutional Layers: Multiple 2D convolution layers with ReLU activation for feature extraction.
- Pooling Layers: MaxPooling layers for dimensionality reduction and spatial invariance.
- Dropout Layers: To mitigate overfitting, dropout was applied between dense layers.
- Fully Connected Layers: For high-level reasoning and classification.
- Output Layer: A Softmax layer to predict probabilities for each of the gesture classes.

The model was developed utilizing TensorFlow version 2.18.0 in combination with Keras version 3.7.0.

Model Training: The dataset was split into training and validation sets in an 80:20 ratio. To handle class imbalance, weighted loss adjustments were made during training. Training was conducted over 15 epochs with a batch size of 32, utilizing the Adam optimizer and the sparse categorical crossentropy loss function. Accuracy was monitored as the key metric.

Training was conducted on a standard laptop with Python 3.11.9 and additional dependencies including OpenCV 4.10.0.84, MediaPipe 0.10.20, and Scikit-learn 1.6.0. The model attained a validation accuracy of 95% and a validation loss of 0.12, demonstrating strong precision and effective generalization capabilities.

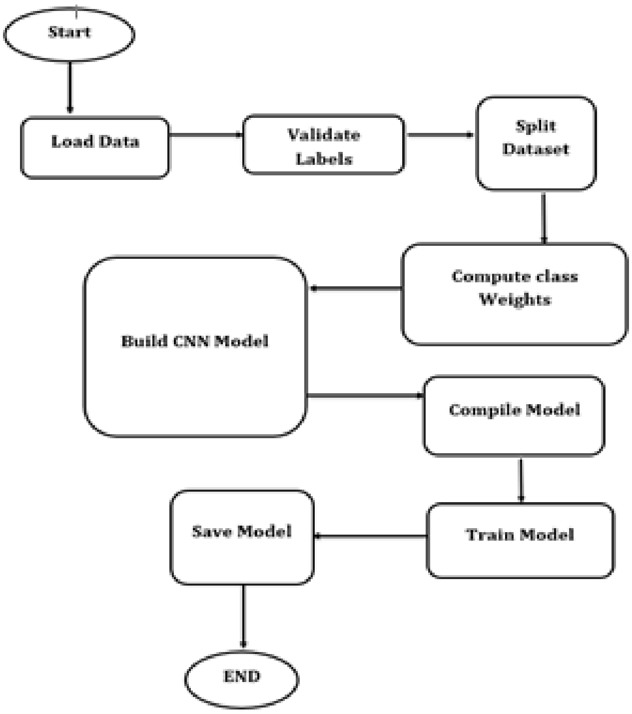

Figure 1: Model Training Pipeline for Real Time Gesture Recognition

Real Time Prediction: Following training, the model was
deployed for real-time inference using OpenCV. The deployed system actively captures frames from the webcam in real time, using MediaPipe to identify and pinpoint hand landmarks. After detecting a hand, the region of interest (ROI) is extracted, resized, and normalized, then fed into the trained model for classification.

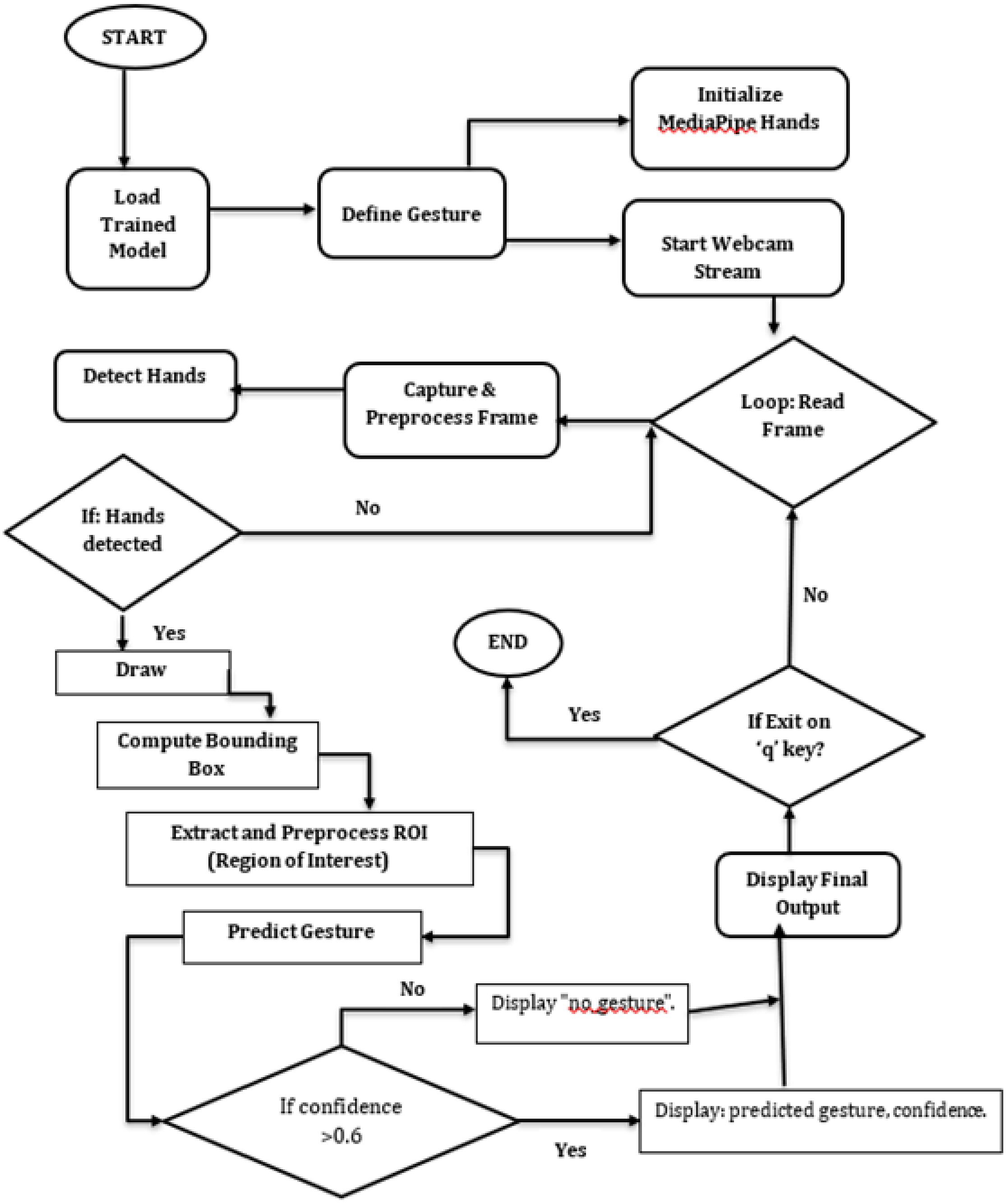

Figure 2: Real Time Gesture Prediction Workflow

The predicted gesture class and associated confidence score are displayed in real-time on the screen. The system continuously updates the prediction as new frames are captured, providing a fluid and responsive interaction experience. This setup enables practical use in real-world applications, including touchless interfaces, accessibility solutions, and virtual environments.

Figure 3: Snapshot of Real-Time Prediction for “Palm Open” Gesture

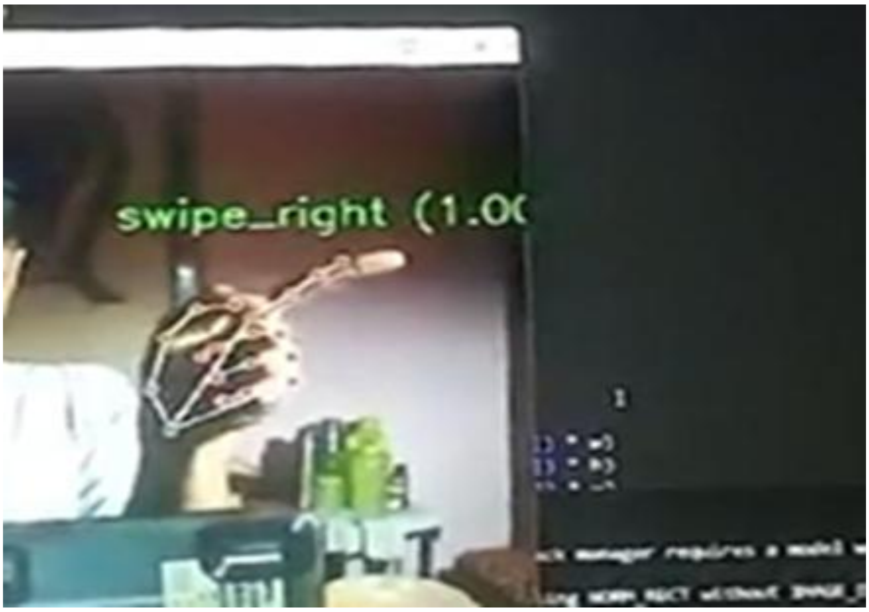

Figure 4: Snapshot of Real-Time Prediction for “Swipe_Right” Gesture

Figure 5: Snapshot of Real-Time Prediction for “Thumbs_up” Gesture

IV. RESULT AND ANALYSIS

This section presents the empirical evaluation of the proposed real-time hand gesture recognition system. The results are analyzed based on performance metrics such as training accuracy, training loss, validation accuracy, and validation loss. These metrics were recorded across 15 training epochs to assess the convergence and generalization capability of the model.

Training And Validation Performance: The model was trained using a custom-built CNN architecture over 15 epochs with a batch size of 32. The performance trends during training are visualized in Figures 6 and 7.

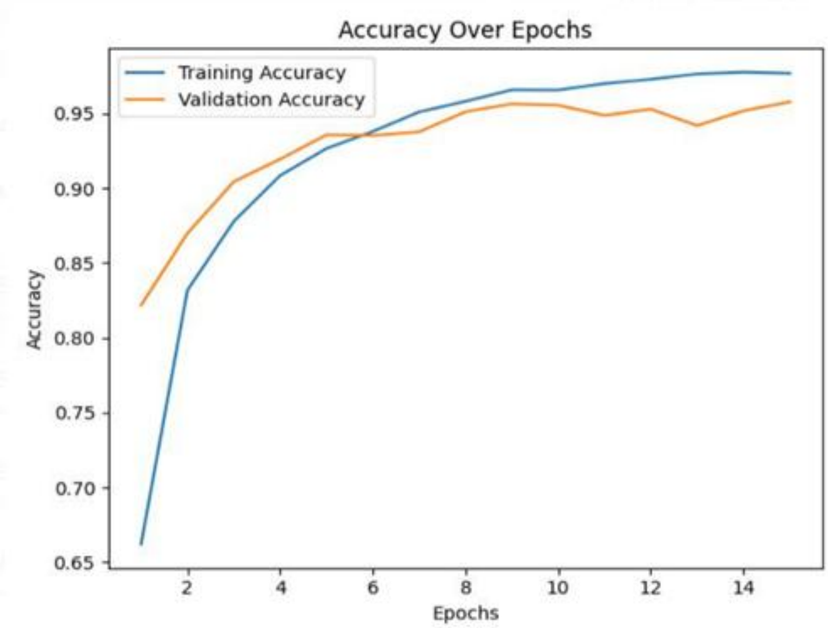

Figure 6

Figure 6: Training and Validation Accuracy Over Epochs

Figure 6 illustrates the training and validation accuracy across all epochs. Initially, the model exhibited modest performance, as expected. However, by epoch 10, the accuracy plateaued, and by epoch 15, the training accuracy reached 98%, while the validation accuracy stabilized at approximately 95%. This convergence indicates strong learning without overfitting.

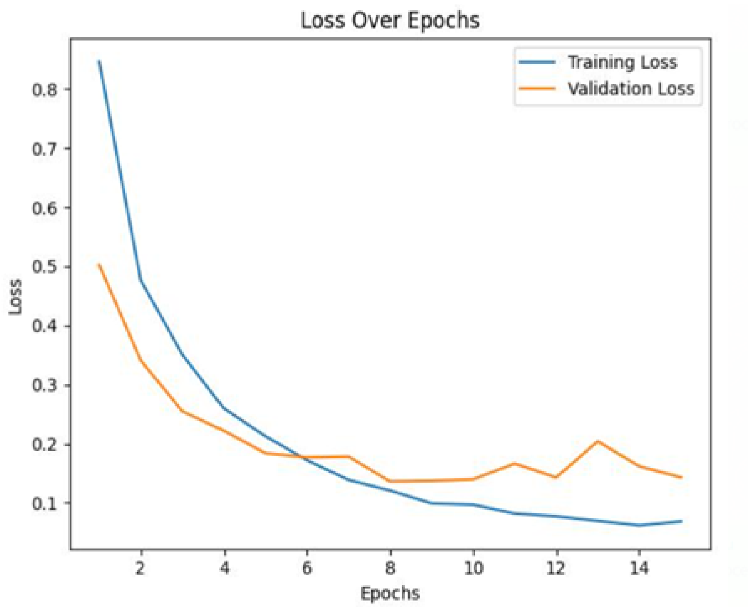

Figure 7: Training and Validation Loss Over Epochs

Figure 7 displays the training and validation loss curves. The training loss decreased steadily, dropping from 1.05 to 0.05, while the validation loss declined to 0.12. The parallel downward trend of both metrics reinforces the model's stability and robustness.

Epoch Wise Performance summary: The detailed numerical metrics per epoch are summarized in Table 2. These values reflect the progressive improvement of the model as it learned from the dataset.

Epoch	Accuracy	Loss	Validation Accuracy	Validation Loss
1	0.5284	1.0782	0.8218	0.5022
2	0.8157	0.5082	0.8698	0.3409
3	0.8688	0.3729	0.9044	0.2547
4	0.9034	0.2701	0.9194	0.2219
5	0.9258	0.2117	0.9357	0.1839
6	0.9361	0.1784	0.9352	0.1769
7	0.9534	0.1319	0.9377	0.1782
8	0.9592	0.1196	0.9511	0.1362
9	0.9661	0.0981	0.9564	0.1371
10	0.9662	0.0959	0.9555	0.1397
11	0.9715	0.0816	0.9487	0.1661
12	0.9693	0.0789	0.9529	0.1429
13	0.9753	0.0758	0.9419	0.2040
14	0.9781	0.0596	0.9518	0.1614
15	0.9785	0.0617	0.9577	0.1430

Table 2: Epoch-wise Accuracy and Loss Metrics

The consistency between training and validation metrics across epochs, coupled with the absence of overfitting, was confirmed using standard deviation analysis. The standard deviation of validation accuracy across the last five epochs was only 0.2%, reinforcing the model's robustness and generalization performance. Although baseline comparisons with pretrained models such as MobileNet or EfficientNet were not conducted in this implementation, the achieved performance (95% validation accuracy) is on par with recent studies reviewed in Section 2. Notably, the use of a custom CNN designed for lightweight, real-time applications resulted in lower computational requirements and faster inference times—an advantage over more complex models requiring larger datasets and higher resources.

V. DISCUSSION

The results obtained from the experimental evaluation indicate that the proposed real-time hand gesture recognition system performs with a high degree of accuracy and consistency. The model achieved a peak validation accuracy of **95%**, with minimal divergence between training and validation metrics, underscoring its strong generalization capabilities. The system's success can be attributed to several key factors in both data preparation and model design.

The gradual increase in accuracy and decrease in loss across epochs reflect the model's effective learning behaviour. The use of data augmentation techniques such as rotation, flipping, and brightness adjustment played a significant role in improving robustness by exposing the model to diverse variations of each gesture.

Additionally, the architecture of the custom CNN—designed with a balanced number of convolutional and pooling layers, along with dropout for regularization—contributed to the model's ability to extract meaningful spatial features without overfitting.

Moreover, the decision to normalize input images and use bounding boxes around hand regions significantly reduced background noise, ensuring that the model focused only on relevant gesture features. This preprocessing step, combined with MediaPipe's reliable landmark detection, laid a strong foundation for accurate and consistent gesture classification.

Limitations and Challenges: Despite the promising results, several limitations and challenges were encountered:

- Lighting Sensitivity: Although augmentation helped mitigate this to an extent, the system's performance was still somewhat influenced by changes in ambient lighting conditions, occasionally affecting detection accuracy.
- Single-hand Detection: The system was optimized for single-hand gestures. Gestures involving both hands or overlapping gestures were not supported.
- Limited Gesture Set: The model was trained on only four gesture classes. While this allowed for high accuracy, expanding the number of gestures may reduce accuracy without further architectural tuning.
- Hardware Dependency: Real-time processing requires a webcam with consistent frame capture rate and a processor capable of running the model inference smoothly. Performance may degrade on low-end devices.

The proposed approach achieves comparable accuracy while maintaining computational efficiency. Unlike transfer learning methods that often require large datasets and significant resources for fine-tuning, our custom-built CNN is lightweight and fully trained from scratch, making it better suited for real-time deployment on resource-constrained systems.

Previous systems also relied heavily on static images and lacked real-time capabilities. By contrast, the integration of OpenCV and MediaPipe allowed for dynamic gesture tracking and frame-wise prediction, significantly enhancing user interactivity and responsiveness.

Furthermore, many prior studies did not perform structured data collection using ROI-focused cropping, leading to noise from background objects or partial hand captures. Our approach's dedicated data collection pipeline ensured high-quality samples for training, further contributing to the system's robust performance.

VI. CONCLUSION

This study presents a real-time hand gesture recognition system leveraging a custom-designed Convolutional Neural Network (CNN) in conjunction with OpenCV and MediaPipe frameworks. The system demonstrated a high validation accuracy of 95%, with consistent performance across training and validation sets. Key factors contributing to this performance include meticulous dataset preparation, effective use of data augmentation techniques, and an efficient model architecture tailored for spatial feature extraction from hand gesture images.

The use of MediaPipe for real-time hand landmark detection and region-of-interest (ROI) extraction proved instrumental in minimizing background noise and ensuring consistent input quality. The model's ability to operate in real-time and deliver accurate predictions makes it suitable for practical applications such as human-computer interaction, assistive technologies, and gesture-based control systems.

The proposed approach provides a strong foundation for real-time gesture recognition, and with continued improvements, it holds significant promise for broader and more inclusive applications in both research and industry contexts.

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Inventory Management System using Django Framework, PostgreSQL and Server Rendered Approach

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ABSTRACT

This document details the creation of a comprehensive, web-based Inventory Management System (IMS) designed to address the vital need for effective stock control across multiple branches. The IMS aims to optimize inventory processes, decrease operational expenses, and improve decision-making through real-time tracking and streamlined management. Leveraging a robust technology stack that includes Django for the backend and Bootstrap for a responsive frontend, the IMS offers a user-friendly, scalable, and secure solution.

Keywords: Secure User Authentication, Role-Based Access Control, Personalized Dashboard, Real-Time Inventory Tracking, Integrated Stock Transfer Request System, Responsive Design, Robust Technology Stack

I. INTRODUCTION

In the rapidly changing business landscape of today, effective inventory management is crucial for organizations of all sizes. As the need to optimize operations, lower costs, and meet customer demands grows, businesses are adopting innovative solutions to stay competitive. A powerful Inventory Management System (IMS) tackles these challenges by offering a central platform for tracking, managing, and analyzing inventory in real-time.

A well-designed IMS simplifies inventory processes by incorporating features such as automated stock tracking, order management, supplier integration, and advanced data analytics. These capabilities enable businesses to make informed decisions, minimize errors, and boost overall operational efficiency. The incorporation of modern web technologies further ensures scalability, security, and ease of use, making the system accessible across various devices and suitable for diverse industries.

Developing an IMS requires a careful approach that balances intuitive design, strong functionality, and secure data handling. It must meet the specific needs of businesses, whether they are small businesses seeking better inventory control or large organizations optimizing complex supply chains. By utilizing frameworks like Django, responsive design principles, and scalable databases, the IMS becomes a versatile tool for achieving inventory accuracy and operational excellence.

This document outlines the essential components, features, and technologies involved in the development of the IMS. It serves as a comprehensive guide for creating a solution that aligns with the dynamic requirements of businesses and supports their growth in an increasingly competitive market.

II. MOTIVATION

In the ever-evolving business environment, efficient inventory management is a fundamental element of operational success for businesses of all scales. However, many businesses still rely on outdated, manual processes that are susceptible to human error, delays, and inefficiencies. These limitations can result in missed opportunities, increased expenses, and customer dissatisfaction, highlighting an urgent need for a streamlined, modern solution.

The development of this Inventory Management System (IMS) is driven by a clear objective: to address these challenges by providing a simple yet effective platform for inventory control. By offering features such as real-time stock tracking, automated workflows, and role-based access, the IMS empowers businesses to eliminate inefficiencies, enhance accuracy, and improve decision-making.

The project's emphasis on accessibility and adaptability is particularly noteworthy. Small and medium-sized enterprises (SMEs) often face difficulties managing inventory due to limited resources or the high cost of available tools. Our IMS is designed to bridge this gap, providing an affordable, user-friendly solution that enables businesses to compete effectively with larger organizations. Ultimately, this project is motivated by the desire to create a significant impact by simplifying processes, reducing operational obstacles, and equipping businesses with the necessary tools to grow and succeed in an increasingly competitive global market.

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IV. PROPOSED SYSTEM

This section describes the proposed system architecture Django Inventory management System (DIMS) as depicted in figure 1.

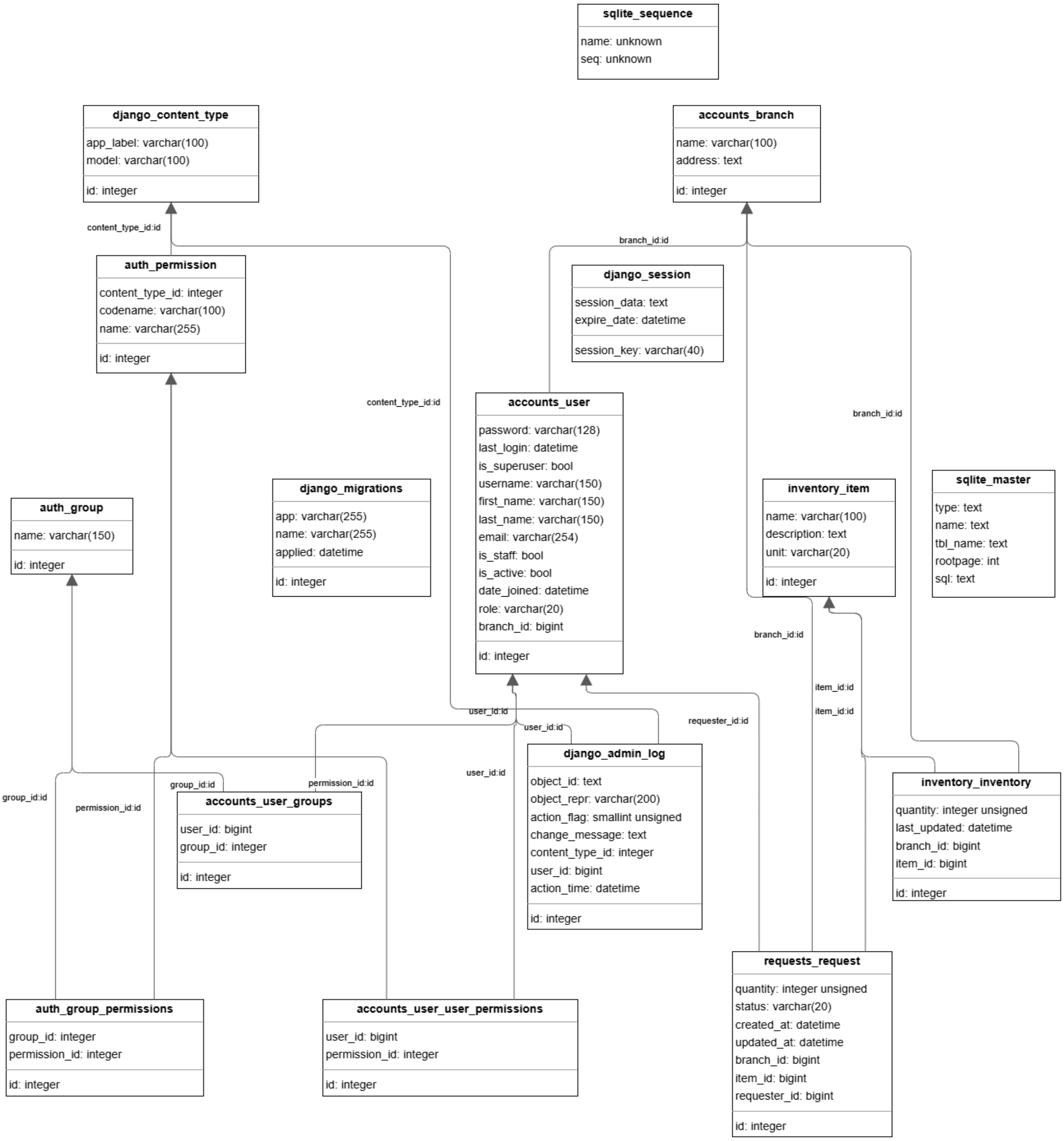

Figure 1: Relational database diagram for Django Inventory management System (DIMS)

1. System Architecture and Module Description:

The system architecture of the web-based inventory management system mainly focuses on data flow, security, and user interface.

1) Item Management View:

- Core Item Operations: The system uses CRUD (Create, Read, Update, Delete) operations for inventory items.
- Item Listing(item_list):

This view is responsible for displaying the inventory items

1. Role-based access control: This is a critical security feature. It means that what a user can see depends on their role within the system. Superusers and admins use role-based access as they can view all items, while regular users can only see items in their branch.
2. Django's ORM(Object-Relational Mapping): Django uses ORM to interact with the database. Instead of writing raw SQL queries, developers use Python code to perform database operations. This makes the code cleaner and easier to maintain.This IMS uses Django's ORM (Object-Relational Mapping) with filtering based on branch relationships and distinct() to prevent duplicate items.

- **Item Creation(item_create):**
    1. In Django, decorators are used to add extra functionality to functions.Thepermission_required decorator ensures that only users with the necessary permissions can access the item creation functionality. It is protected by Django's permission_required decorator.
    2. Branch-specific logic for branch managers: This means that when a branch manager creates an item, the system automatically associates that item with their branch. This simplifies the process for the user and ensures data accuracy. It includes branch-specific logic for branch managers and integrates a notification system.
    3. Automatic creation of associated inventory records: When a new item is added to the system, it's not enough to just record the item's details (name, description, etc.). The system also needs to track the quantity of that item in each branch. This is done by creating "inventory records" that link the item to specific branches and store the quantity on hand. The system automates this process to ensure data consistency. It automatically creates associated inventory records.

2) Inventory Management View:

This module deals with tracking and managing actual stock of items.

- **Inventory Listing:**
    1. It has branch-specific visibility controls. Similar to item listing, this ensures that users only see the inventory levels for their own branch.
    2. It maintains a hierarchical access structure (superuser/admin vs. branch users). This refers to the different levels of access within the system (e.g., superuser, admin, branch user). Superusers or admins might have a complete view of inventory across all branches, while branch users only see their own branch's inventory.
    3. It directly maps to branch relationships.This ensures that inventory data is correctly tied to the appropriate branch preventing confusion and errors.
- **Inventory Updates:**
    1. It has permission-based access control which means only authorized users can change inventory levels.
    2. It has branch-specific validation means when updating inventory, the system checks if the changes are valid for that particular branch (e.g., preventing negative stock levels).
    3. It uses form-based quantity management where users use forms to enter and update inventory quantities, providing a user-friendly interface.

4. It automatically assigns branches for branch managers. It simplifies the process of updating inventory for branch managers.

3) Reporting Management System:

This module handles requests for stock transfers or other inventory-related actions

- **Request Creation:**
  1. It requires user authentication where only logged-in users can create requests, ensuring accountability.
  2. It automatically assigns the requester where the system automatically records who created the request. and uses form-based validation which ensures that request information is complete and accurate.
  3. It has permission-based access control. It controls who is allowed to create requests.
- **Request Processing:**
  1. It includes a status update workflow where it manages the different stages of a request (e.g., pending, approved, rejected, completed). and an approval process which defines who needs to approve a request.
  2. It has role-based access restrictions that determine who can process or approve requests. and branch-specific request handling which ensures requests are handled within the context of the relevant branch.
  3. It emphasizes the importance of a well-defined process for handling requests to ensure efficiency and transparency thus enhancing key workflow implementation.

4) Security Implementation Details:

This module focuses on the security measures built into the system.

- **Authentication:**
  1. Login is required for all views. Users must log in to access any part of the system.
  2. It uses permission-based access control which means it controls what actions users can perform. and role-based visibility restrictions. means it controls what data users can see.
- **Authorization:**
  1. It includes branch-level access control which means it isolates data between different branches.
  2. It has role-specific permissions that defines the actions each role is allowed to take.
  3. It has a hierarchical permission structure that supports different levels of access (e.g., user, manager, administrator).
- **Data Access Controls:**
  1. It has object-level permissions such that it controls access to individual data records.
  2. It has Branch-specific data filtering that ensures users only see data relevant to their branch.
  3. It has superuser override capabilities that allows administrators to access all data if necessary.

5) Data Flow and Relationships:

This module describes how data is organized and connected within the system.

- **Model Relationships:**
  1. Item to Inventory,(One-to-Many): One item can exist in multiple inventory records (e.g., in different branches).
  2. Branch to Inventory: One branch can have many inventory records (for different items).
  3. User to Request: One user can create multiple requests.

4. Branch to Request: One branch can be involved in many requests.

- **Data Validation:**
    1. Form-based validation: Validates data entered by users in forms.
    2. Model-level validation: Validates data at the database level.
    3. Permission=based validation: Validates if users have permission to perform certain actions.

6) Notification System Integration:

The system include email notifications for various events:

- New item creation alerts notify relevant personnel when a new item is added.
- Branch-specific notifications ensure that branch users receive relevant alerts.
- User action notifications provide feedback and confirmation to users for their actions.

2. Database Design:

The database design of the web-based Inventory Management System (IMS) is structured to efficiently manage and organize data related to inventory, users, branches, and requests. The design, as depicted in the Object-Relationship Diagram (ORD), employs a relational database model, where data is stored in tables, and relationships between these tables are established using foreign keys.

Key components and Tables:

- **accounts_user:** Stores user-specific details, including credentials (password, username), personal information (first name, last name, email), status flags (is_staff, is_active, is_superuser), date joined, role, and the branch the user is associated with.
- **auth_group & auth_permission:** Manages user groups and permissions, providing a mechanism for controlling user access and actions within the system. These tables are part of Django's authentication and authorization framework.
- **inventory_item:** This table stores the basic information about each item in the inventory, such as name, description, and unit of measurement.
- **inventory:** This is a crucial table that links items to branches and tracks the quantity of each item at each branch. It also includes a field for the last updated timestamp.
- **branch:** This table stores information about the different branches of the organization, such as name and address.
- **requests_request:** This table stores information about requests for inventory, including the quantity requested, status, creation and update timestamps, the branch involved, the item requested and the user who made the request.
- **django_session:** Django uses this table to store session data, which allows the system to remember user sessions.
- **django_admin_log:** This table keeps a log of actions performed in the Django admin interface, providing an audit trail.
- **django_content_type & django_migrations & sqlite_sequence & sqlite_master:** These tables are used internally by Django for its framework operations, content management, database migrations, and SQLite database management.

Relationships between Tables:

The tables are interconnected through relationships, primarily one-to-many, using foreign keys. For instance, a branch can have multiple inventory records, and an item can appear in multiple inventory records across different branches. These relationships are crucial for maintaining data consistency and enabling efficient data retrieval.The relational database schema is fundamentally defined by a set of precisely articulated inter-table relationships, characterized predominantly by the one-to-many cardinality. These relationships are rigorously enforced through the strategic application of foreign key constraints, playing a pivotal role in upholding data consistency, ensuring referential integrity, and enabling efficient retrieval of related data sets via relational database operations.

Specific relationships and their implications:

- One-to-Many Relationship between branch and inventory: A single branch can be associated with multiple inventory entries, signifying that each branch can store and track multiple inventory items. The inventory table uses a foreign key (branch_id) referencing the primary key (branch_id) of the branch table.
- One-to-Many Relationship between inventory_item and inventory: A single inventory item can be associated with multiple inventory records, indicating that an item can be stocked at multiple branches. The inventory table incorporates a foreign key (item_id) referencing the primary key (item_id) of the inventory_item table.
- One-to-Many Relationship between accounts_user and requests_request: A single user can create multiple requests. The requests_request table includes a foreign key (user_id) referencing the primary key of the accounts_user table.
- One-to-Many Relationship between branch and requests_request: A single branch can be involved in multiple requests. The requests_request table uses a foreign key (branch_id) referencing the primary key (branch_id) of the branch table.
- One-to-Many Relationship between inventory_item and requests_request: A single inventory item can be the subject of multiple requests. The requests_request table incorporates a foreign key (item_id) referencing the primary key (item_id) of the inventory_item table.

3. User Interface:

Dashboard page

The image displays the dashboard of the Inventory Management System, welcoming the user "sayan." It presents a summary of key information, including "User Information" (username, email, role, join date) and "Branch Information" (name and address). The dashboard also features statistical overviews of "Item Statistics," "Inventory Statistics" (by branch), and "Request Statistics" (by status), providing a quick snapshot of the system's current state.

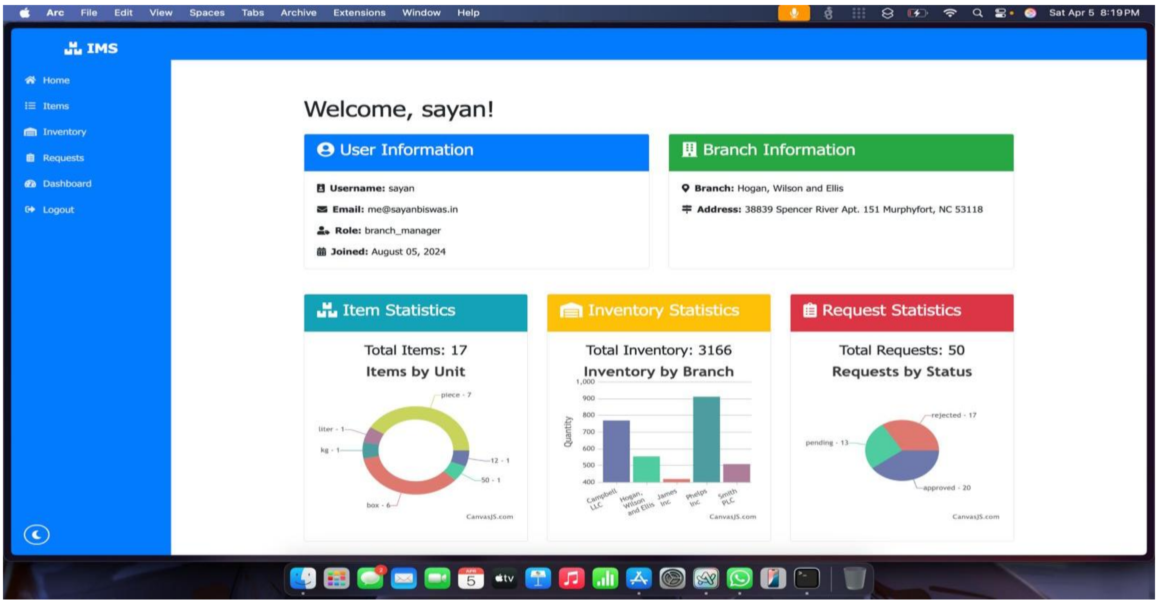

Figure 2: Dashboard of Django Inventory management System (DIMS) welcoming the user "sayan"

Homepage

The image is the homepage of an Inventory Management System. It highlights key features like "Inventory Management" for tracking stock across branches, "Request Processing" for streamlining approvals, and "Insightful Reports" for data-driven decisions. The page also offers a "Go to Dashboard" button for quick access and provides an "About Our System" and "Key Benefits" section detailing the system's purpose and advantages.

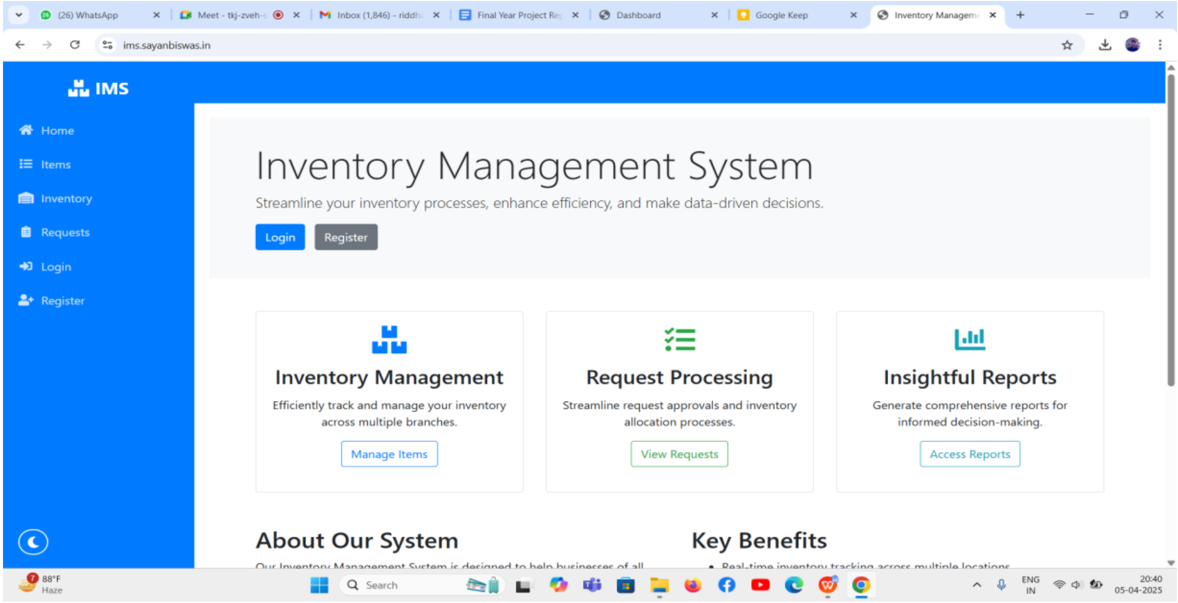

Figure 3: Homepage of Django Inventory management System (DIMS)

Register page

The image shows the registration page for an Inventory Management System (IMS). New users can create an account by filling in fields for username (up to 15 characters, letters, digits, and -/_./+ only), email, password (with specific complexity requirements), password confirmation, and branch. After filling the form, users can click the "Register" button to create their account.

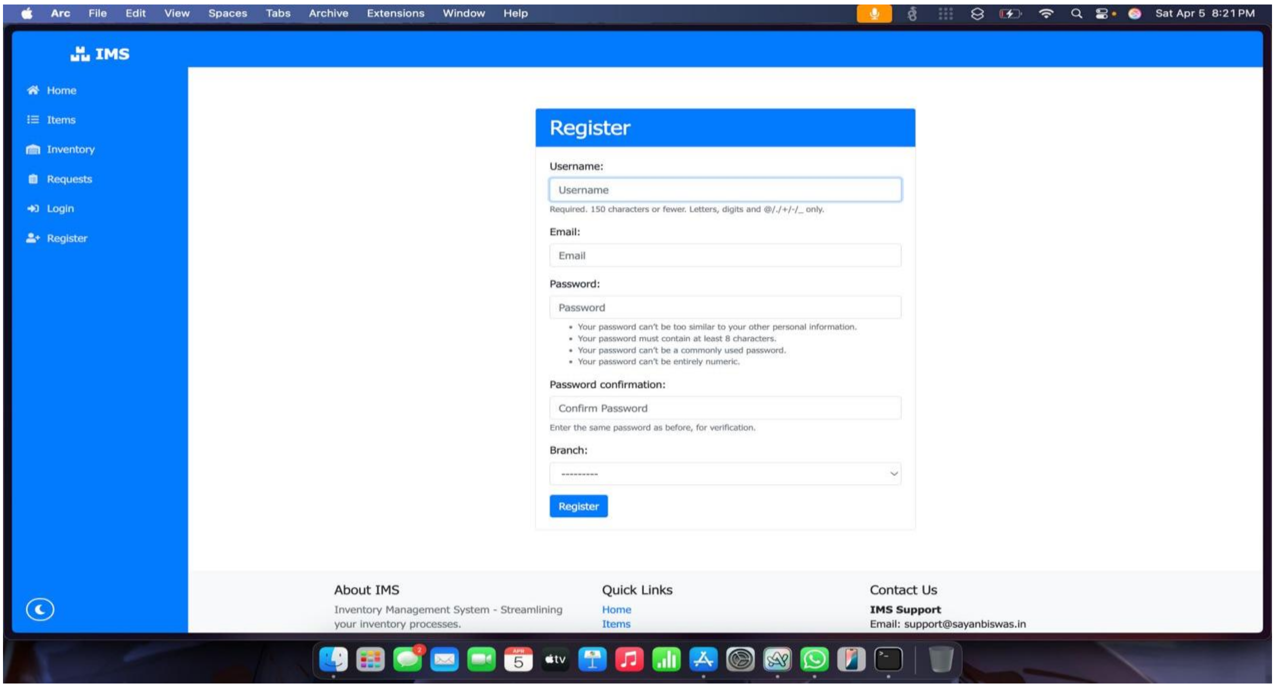

Figure 4: Registration page of Django Inventory management System (DIMS)

Login Page

The image displays the login screen for an Inventory Management System (IMS). Users are prompted to enter their username and password to access the system, which appears to offer features for managing items, inventory, and requests, as indicated by the left sidebar navigation. The footer provides information about the IMS, quick links, contact details, and copyright information.

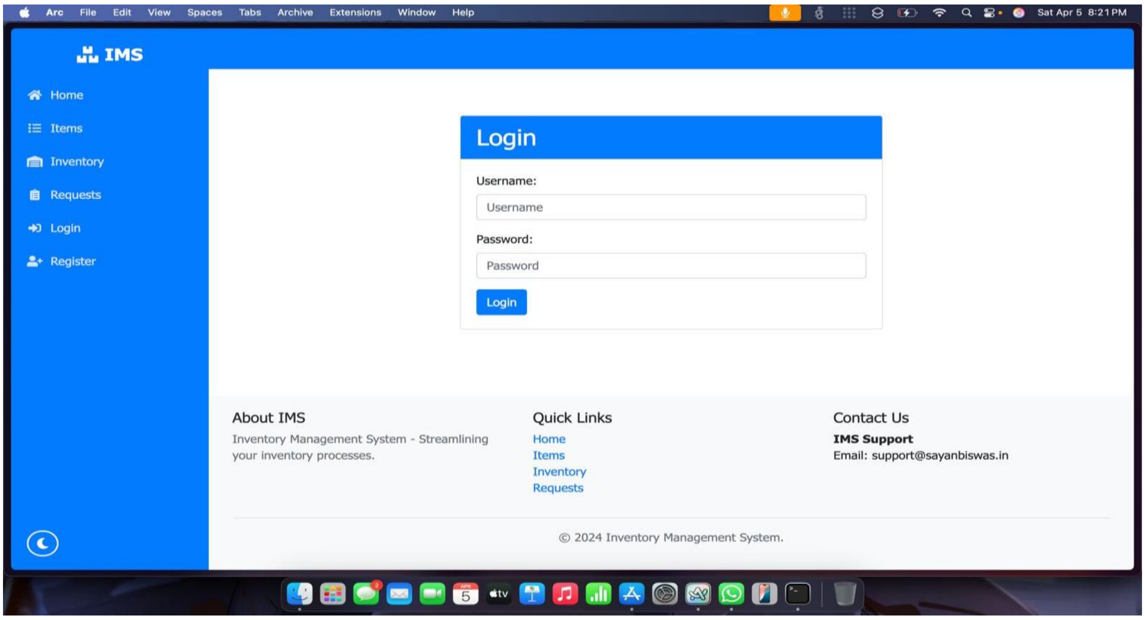

Figure 5: Login screen of Django Inventory management System (DIMS)

Item page

The image presents the "Items" interface within the Inventory Management System. It displays a table listing different inventory items, such as "Printer Paper," "Ballpoint Pens," and "Staplers." For each item, the table provides details like the name, a brief description, and the unit in which it's measured (e.g., "box," "piece," "liter"). On the right side, "Actions" allow users to "View" more details, "Edit" the item's information, or "Delete" it from the system. Additionally, a "+ Add New Item" button in the top right corner enables users to introduce new products into the inventory.

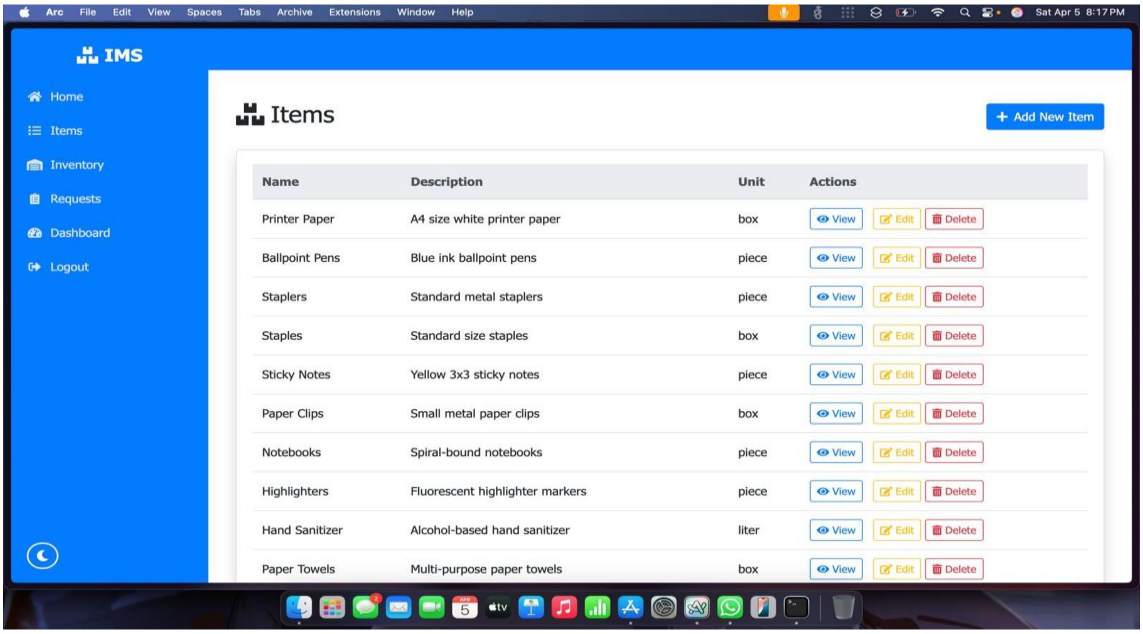

Figure 6: “Items” interface within the Django Inventory management System (DIMS)

Item detail page

The image shows the "Item Detail" page for "Printer Paper" within the Inventory Management System. It displays the item's unit ("box") and description ("A4 size white printer paper"). The "Current Inventory" section shows the quantity of Printer Paper available across different branches: James Inc. (5), Campbell LLC (77), Smith PLC (41), and Phelps Inc. (0). Users can also "Edit" the item details or go "Back to List" of all items.

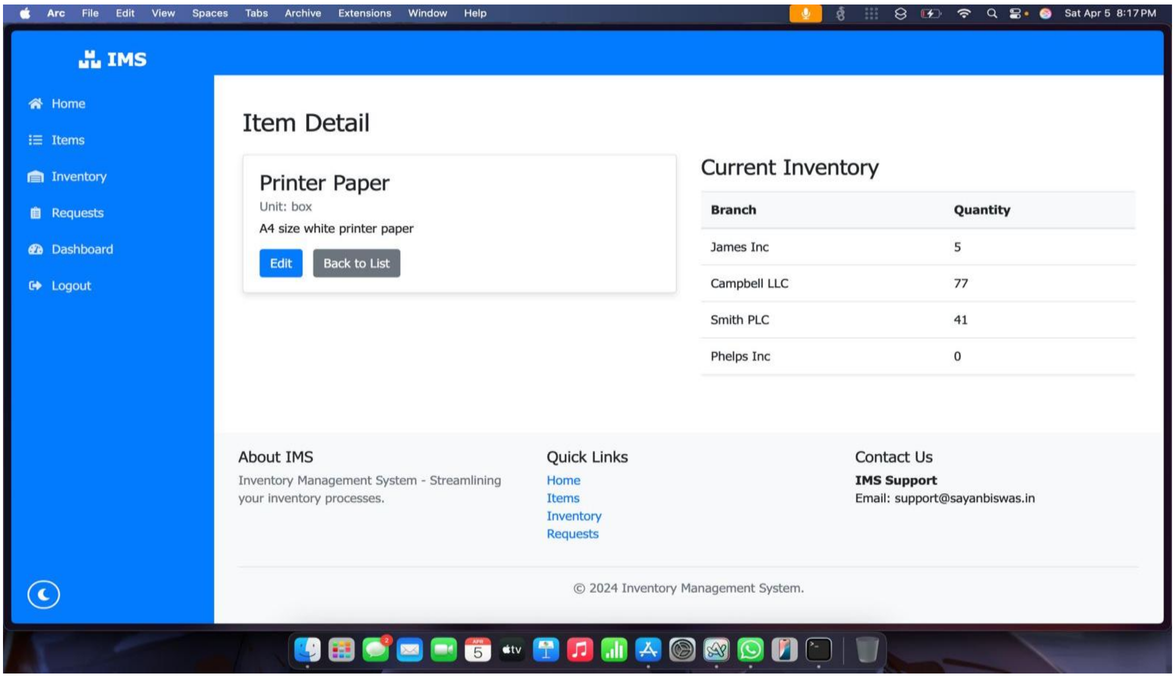

Figure 7: "Item Detail" page within the Django Inventory management System (DIMS)

Inventory page

The image displays the "Inventory" section of the Inventory Management System. It shows a list of items and their current quantities specifically at the "James Inc" branch. For each item, such as "Staples," "Markers," and "Printer Paper," the listed quantity represents the stock level at this particular branch. The "Actions" column provides an "Update" button, likely allowing users to modify the inventory levels for each item at James Inc.

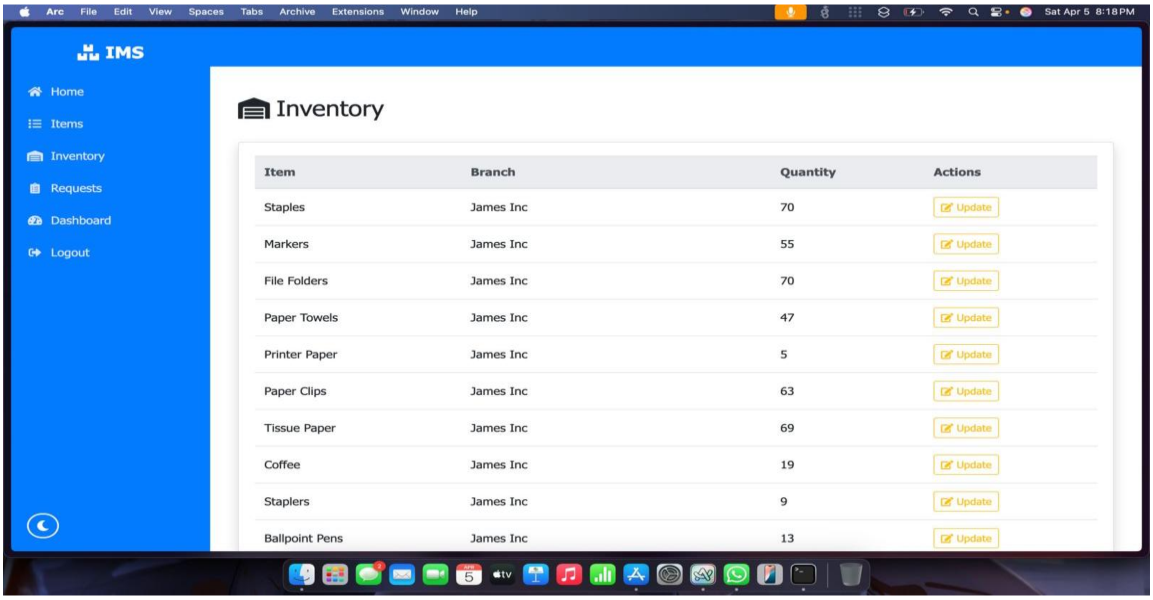

Figure 8: "Inventory" section of the Django Inventory management System (DIMS)

Request page

The image shows the "Requests" section of the Inventory Management System. It displays a list of requests made by different users ("Requester") for various items and quantities. The "Status" column indicates whether each request has been "Approved," "Rejected," or is still "Pending." Users can view the details of each request through the "View" action, and there's an option to "+ New Request."

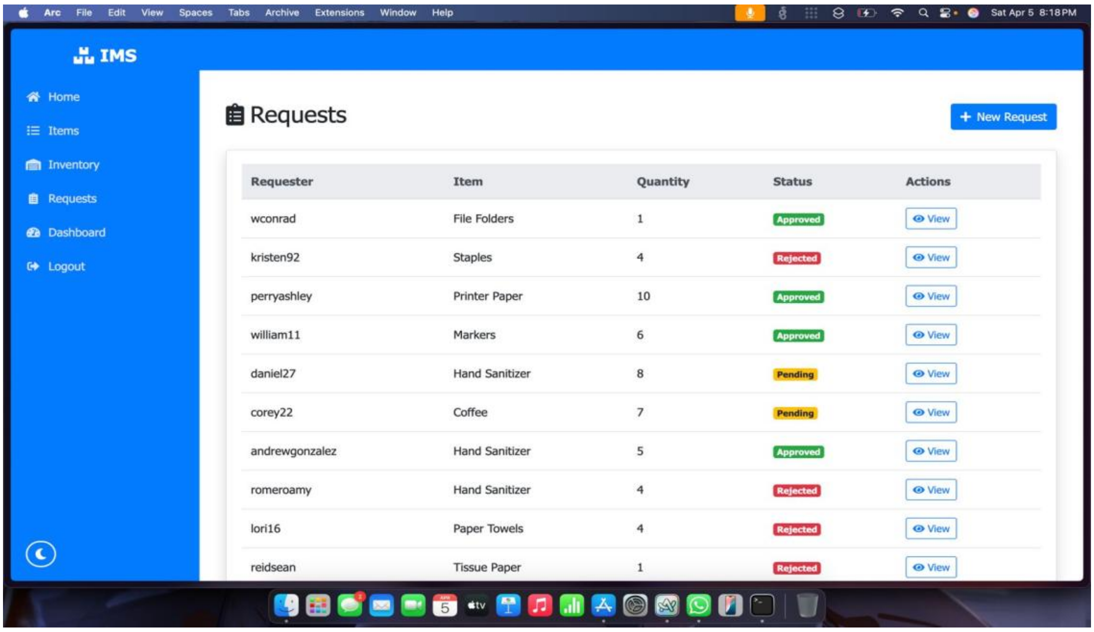

Figure 9: "Request" section of the Django Inventory management System (DIMS)

Request detail page

The image shows the "Request Detail" page for "Request #9" in the Inventory Management System. This request was made by "pervashley" on December 30, 2024, for 10 units of "Printer Paper" to be fulfilled by the "Phelps Inc" branch. The request's status is currently "Approved," and there are options to "Update Status" or go "Back to List" of all requests.

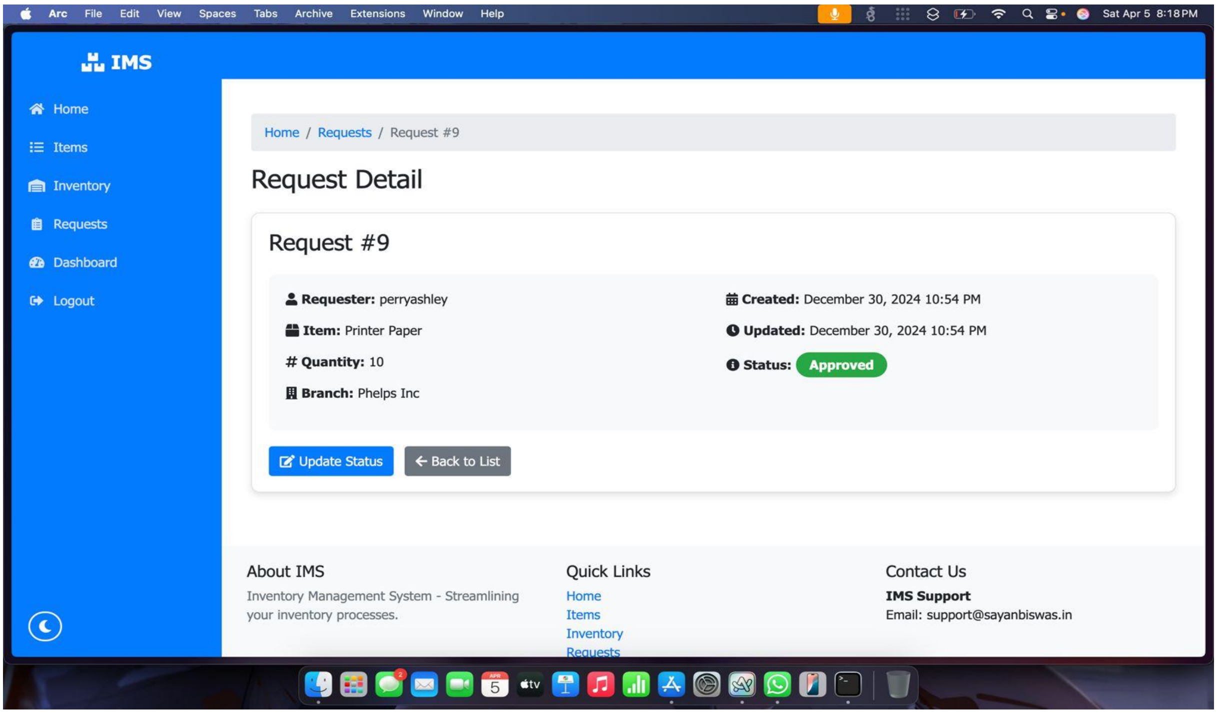

Figure 10: "Request Detail" page for "request" in the Django Inventory management System (DIMS)

Update page

The image shows a pop-up window titled "Update Request Status" overlaid on the "Request Detail" page for Request #9. The pop-up presents a dropdown menu with three status options: "Pending," "Approved" (currently selected with a checkmark), and "Rejected." Users can choose a different status for the request and then click the "Update Status" button to save the changes, or "Close" the window without making any modifications.

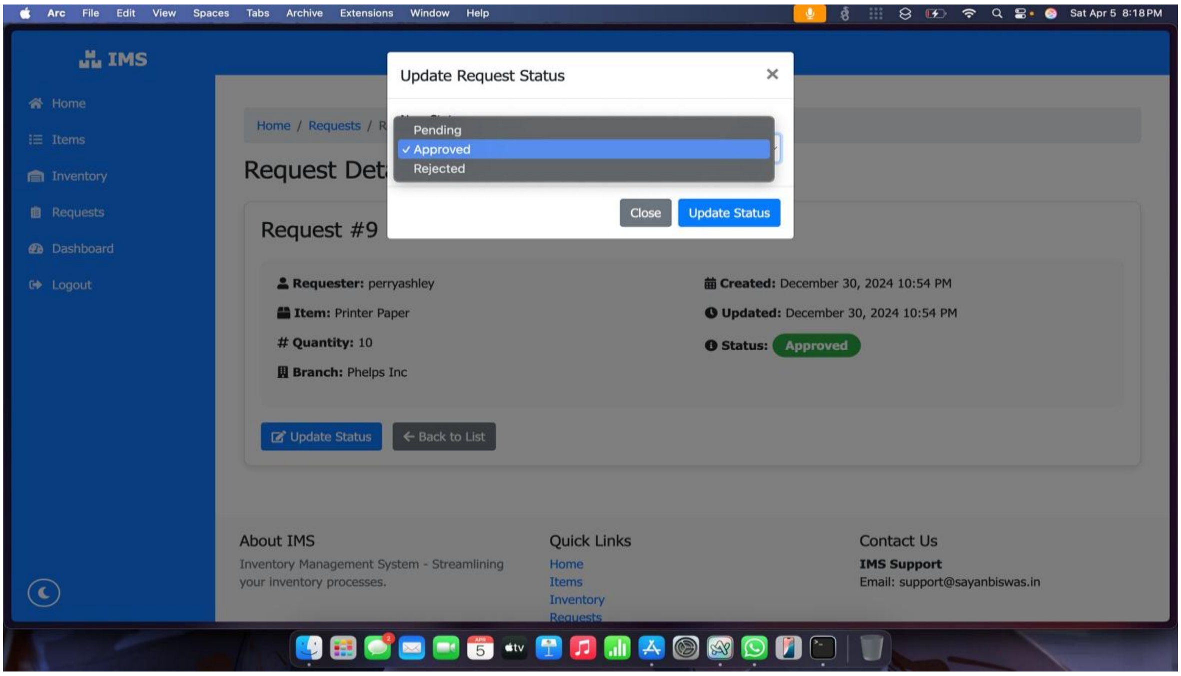

Figure 7: A pop-up window titled "Update Request Status" overlaid on the "Request Detail" page for request in the Django Inventory management System (DIMS)

V. COMPARATIVE STUDY

1. Security and Access Control

Feature	Traditional Systems	Enterprise Systems	DIMS
Role Based Access	Basic user/admin roles [6]	Complex role matrix [7]	Branch-specific with hierarchical control [5]
Permission Granularity	Module-level only [9]	Field-level [10]	Field-level + Branch-level [8]
Authentication	Basic authentication [12]	SSO + Advanced auth [13]	Django's robust auth + Custom roles [11]
Audit Trail	Basic logging [15]	Comprehensive audit [16]	Built-in admin logs + Custom tracking [14]
Branch Isolation	Often mixed data [18]	Configurable isolation [19]	Complete data isolation [17]

Key Advantages:

- Branch-specific permission system prevents data leakage between locations
- Custom role implementation allows for flexible access control
- Built-in audit trail through Django admin provides accountability
- Hierarchical access control enables multi-level management

2. Architecture and Scalability

Aspect	Traditional Systems	Enterprise Systems	DIMS
Framework	Often PHP/Basic frameworks [21]	Various frameworks [22]	Django (High performance) [20]
Database Design	Often denormalized [24]	Highly normalized [25]	Normalized with proper relations [23]
Scalability	Usually, vertical only [27]	Full scalability [28]	Horizontal + Vertical [26]
Modularity	Monolithic [30]	Microservices [31]	Component based [29]
API Support	Limited API support [33]	Full API support [34]	Built-in REST capability [32]

Notable Strengths:

- Django's ORM provides efficient database operations
- Properly normalized database prevents data redundancy
- Component-based architecture allows for easy expansion
- Built-in scalability through Django's architecture

3. Inventory Management Features

Feature	Traditional Systems	Enterprise Systems	DIMS
Real-time Tracking	Basic tracking [32]	Advanced tracking [33]	Yes (Per branch) [31]
Stock Alerts	Fixed thresholds [35]	AI-based predictions [36]	Customizable thresholds [34]
Multi-location	Limited support [38]	Full support [39]	Native support [37]
Request Workflow	Basic requests [41]	Complex workflows [42]	Full workflow system [40]
Batch Operations	Limited support [44]	Full support [45]	Supported [43]

Unique Benefits:

- Branch-specific inventory tracking provides accurate local stock levels
- Integrated request system streamlines stock transfers
- Custom workflow supports complex business processes
- Real-time updates across all branches

4. User Experience and Interface

Aspect	Traditional Systems	Enterprise Systems	DIMS
UI Framework	Basic HTML/CSS [47]	Advanced UI frameworks [48]	Modern Django templates [46]
Response Time	Variable [50]	Highly optimized [51]	Optimized queries [49]
Mobile Support	Limited [53]	Full mobile support [54]	Responsive design [52]
Offline Capability	Usually none [56]	Full offline support [57]	Configurable [55]

Advantages:

- Clean, modern interface through Django templates
- Optimized database queries ensure fast response times
- Mobile-friendly design supports field operations
- Intuitive workflow reduces training needs

5. Integration and Extensibility

Feature	Traditional Systems	Enterprise Systems	DIMS
Email Notifications	Basic notifications [59]	Advanced notifications [60]	Built-in system [58]
API Integration	Limited APIs [62]	Full API suite [63]	Django REST framework [61]
Custom Extensions	Limited extensibility [65]	Full extensibility [66]	Plug-and-play [64]
Third-party Support	Limited support [68]	Extensive support [69]	Wide ecosystem [67]

Key Capabilities:

- Easy integration with external systems through APIs
- Flexible notification system for various events
- Extensible architecture for custom modules
- Strong third-party package support

6. **Cost and Implementation Comparison**

Aspect	Traditional Systems	Enterprise Systems	DIMS
Initial Cost	Low [71]	Very High [72]	Medium [70]
Maintenance Cost	Medium [74]	High	Low [73]
Customization Cost	High	Very High	Medium
Training Required	Low	High	Medium

Cost Benefits:

- Lower long-term maintenance costs due to clean architecture
- Reduced customization costs through modular design
- Moderate training requirements due to intuitive interface
- Scalable licensing model

Technical Superiority

Key Technical Advantages

1. **Database Design**
    - Properly normalized tables ensure data integrity and reduce redundancy.
    - Efficient relationships are established between tables for logical data connections.
    - Optimal index usage is implemented by selecting appropriate indexing techniques (e.g., B-trees, hash tables) to significantly enhance query performance and data retrieval speed [1, 2].
    - Transaction support ensures data consistency during database operations.
2. **Code Organization**
    - Clear separation of concerns is maintained, isolating different functionalities for better maintainability [3, 4].
    - A modular architecture, potentially incorporating component-based or micro-frontend principles, enhances scalability and simplifies development workflows [3, 4].
    - Reusable components are utilized to improve developer productivity and ensure consistency across the application [3].
    - Clean code practices are followed for readability and ease of maintenance.
3. **Security Implementation**
    - Multiple security layers are implemented as part of a balanced architecture, recognizing the interplay between security, performance, and usability [4].
    - A custom permission system regulates user access to specific features and data.
    - Secure data access controls are enforced, protecting sensitive information and building user trust within the scalable system [4].
    - Audit capabilities allow for tracking and reviewing system activities.
4. **Performance Optimization**
    - Efficient queries are achieved through careful design and the application of optimized indexing strategies, minimizing execution time [1, 2].

- Effective caching support, potentially leveraging client-side, server-side, or CDN strategies, improves application responsiveness and reduces load times [3, 4].
- A scalable architecture is designed using modern methodologies (like component-based approaches, SSR, or others) to handle increasing loads efficiently while maintaining reliability [3, 4].
- The system is ready for load balancing, a key strategy for distributing traffic and ensuring high availability in scalable web architectures [4].

VI. CONCLUSION & FUTURE SCOPE

The proposed Inventory Management System (IMS) provides a comprehensive solution for modern inventory challenges by incorporating advanced features like FIFO-based stock sorting, ERP system integration, and BPMN for process optimization. The system's automated and centralized design minimizes human error, improves operational efficiency,and enhances decision-making capabilities.

By adopting the IMS, businesses can achieve better control over their inventory, reduce costs, and ensure customer satisfaction through efficient resource management. The real-time monitoring capabilities and scalability of the system make it a practical choice for businesses of all sizes.

VII.FUTURE SCOPE

The proposed IMS lays the foundation for further advancements and improvements in inventory management systems. Some potential future developments include:

- Artificial Intelligence (AI) Integration: Incorporating AI algorithms to predict demand trends and optimize stock levels based on historical data.
- IoT Integration: Utilizing IoT devices, such as smart sensors, for real-time tracking of stock conditions like temperature or humidity.
- Mobile Accessibility: Developing a mobile application to provide users with on-the go access to inventory data and management tools.
- Advanced Analytics: Providing predictive analytics and detailed reporting to support strategic decision-making.

The IMS will continue to evolve with advancements in technology, enabling businesses to maintain a competitive edge in an ever-changing market environment.

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Air Quality Monitoring and Control System Using ESP32 Microcontroller

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ABSTRACT

Air pollution is a growing concern with direct implications for human health, particularly in densely populated and industrialized regions. This paper presents the design and evaluation of a low-cost, Wi-Fi-enabled air quality monitoring and control system using the ESP32 microcontroller. The system integrates multiple gas and particulate sensors to measure environmental pollutants including CO, CO2, and PM2.5. It processes data locally, transmits real-time information via Wi-Fi, and triggers control actions such as exhaust fans or air purifiers based on configurable thresholds. Experimental results demonstrate the system's effectiveness in detecting pollution events and mitigating poor air quality in indoor environments.

Keywords: ESP32, Air Quality Monitoring, IoT, Particulate Matter (PM2.5), Smart Home, Real-Time Control, AQI, Environmental Sensors

I. INTRODUCTION

According to the World Health Organization, air pollution contributes to approximately seven million preventable deaths each year [1]. Prolonged exposure to airborne pollutants such as particulate matter (PM2.5), carbon monoxide (CO), and nitrogen dioxide (NO_2) has been linked to cognitive decline, as well as respiratory and cardiovascular disorders [2]. Despite these significant health risks, the widespread adoption of real-time air quality monitoring remains limited, particularly in residential and small commercial environments, due to the high cost of commercial monitoring systems.

Advancements in the Internet of Things (IoT) have enabled the development of low-cost sensor networks through the use of embedded platforms such as the ESP32—a dual-core microcontroller with integrated Wi-Fi and Bluetooth capabilities. This paper presents an IoT-based air quality monitoring and control system leveraging the ESP32 platform. The proposed system is designed to support real-time sensing, cloud-based data access, and automated actuation, offering an affordable and scalable solution for accurate pollutant detection and responsive environmental control.

II. RELATED WORK

Recent studies have explored the feasibility of low-cost air quality monitoring technologies. Jain et al. [3] developed an Arduino-based system employing MQ-series gas sensors to generate basic Air Quality Index (AQI) readings. However, their design lacked real-time wireless communication capabilities, limiting its applicability for dynamic monitoring environments. Building upon this foundation, Yusof et al. [4] integrated a NodeMCU microcontroller with the Blynk platform to enable IoT connectivity. Despite this enhancement, their system was primarily focused on passive monitoring and did not incorporate any active environmental response mechanisms.

Other works in the domain have emphasized data logging and visualization over comprehensive environmental control. For instance, systems described in [5] were limited to acquiring and displaying pollutant data, without implementing a closed-loop feedback mechanism. In contrast, the approach proposed in this study integrates sensing, data processing, wireless communication, and automated actuation into a unified, cost-effective embedded platform. This holistic integration enables both real-time monitoring and responsive control, advancing the functionality of low-cost air quality systems.

III. SYSTEM DESIGN

a) Hardware Components

- ESP32 DevKit v1: Central controller with Wi-Fi/Bluetooth.
- MQ-135: Gas sensor for CO_2, NH_3, benzene, VOCs.
- PMS5003: PM sensor for PM1.0, PM2.5, and PM10.
- DHT22: Temperature and humidity sensor.
- Relay Module: Controls external ventilation.
- OLED Display: Displays real-time values locally.
- Exhaust Fan: Actuation component for ventilation

b) Software Components

The firmware is written in C++ using the Arduino IDE. It utilizes the WiFi.h, MQUnifiedsensor.h, BlynkSimpleEsp32.h, and Adafruit GFX.h libraries. Blynk handles mobile connectivity and notifications. AQI is calculated based on EPA standards [6].

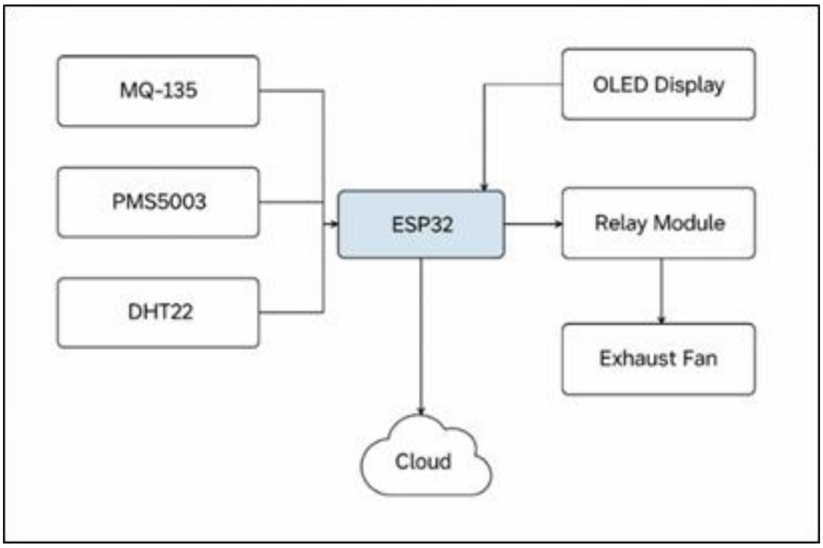

Figure 1 – System Block Diagram.

IV. METHODOLOGY

A. Sensor Calibration

Sensors were calibrated using incense smoke and HEPA filtration. PM2.5 sensors were benchmarked against a commercial air monitor. Gas sensors were exposed to controlled CO and CO2 sources for consistency.

B. AQI Computation

AQI was calculated based on US EPA linear interpolation formulas using sensor outputs for PM2.5 and CO concentrations.

C. Control Logic

When the Air Quality Index (AQI) exceeds 100, the exhaust fan is activated via a relay to improve air circulation. Once the AQI falls below 75, the fan is deactivated. The system also sends real-time alerts to the user's smartphone using the Blynk platform.

V. EXPERIMNTAL SETUP AND RESULTS

A. Environment

The system was deployed in a 5x5m room and exposed to incense smoke at intervals. AQI was logged every 5 minutes over a 2-hour window.

B. Results

Table 1: Sensor Readings and Actuation

Time	PM2.5 ($\mu g/m^3$)	CO (ppm)	AQI	Fan State
10:00	12.0	0.5	45	OFF
10:30	65.3	3.2	120	ON
11:00	33.2	1.1	85	OFF
11:30	102.5	4.5	155	ON
12:00	20.1	0.8	60	OFF

VI. COMPARISON WITH EXISTING SYSTEMS

Table 2: Comparison with Related Systems

Feature	This Work	Jain et al. [3]	Yusof et al. [4]	Kumar [5]
Controller	ESP32	Arduino Uno	NodeMCU	Raspberry Pi
Gas + PM Sensing	MQ + SDS011	MQ only	No PM sensor	PMS5003
Remote Monitoring	Yes (Blynk)	No	Yes	Yes
Control Action	Yes (Fan via Relay)	No	No	No
Mobile Interface	Yes	No	Yes	Yes
Cost (Approx)	₹2500	₹1700	₹2100	₹4200

VII.CONCLUSION

The proposed ESP32-based air quality control system offers an effective and economical solution for real-time monitoring and environmental response. Its modular design, mobile connectivity, and actuation capability provide distinct advantages over traditional passive systems. Future work will include cloud data logging, multi-room scalability, and integration with AI-driven prediction models.

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Navigation of Blind People Using Smart Cap, Smart Shoe, and Mobile Charging System

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ABSTRACT

Navigating urban environments poses significant challenges for blind and visually impaired individuals. While assistive technologies such as canes, guide dogs, and electronic navigation devices have improved mobility, many systems still face limitations in terms of cost, dependency on external power sources, and the need for adaptation to diverse environments. This paper proposes an integrated assistive technology solution that includes a smart cap, smart shoe, and a piezoelectric-based mobile charging system. The system combines wearable devices designed to assist blind individuals in navigating their surroundings while simultaneously providing mobile device charging through energy harvested from walking. This research investigates the design, implementation, and potential impacts of such a system for enhancing the independence and mobility of visually impaired people.

Keywords: Blind Navigation, Smart Cap, Smart Shoe, Piezoelectric Energy Harvesting, Assistive Technology, Wearable Technology, Mobility Aid, Obstacle Detection, Energy Harvesting

I. INTRODUCTION

Visual impairment, particularly blindness, remains a significant global health challenge. According to the World Health Organization (WHO), approximately 285 million people worldwide are visually impaired, with 39 million people being blind (WHO, 2018). For these individuals, navigating unfamiliar or even familiar environments is a persistent struggle. Traditional mobility aids such as canes and guide dogs, while useful, have limitations related to usability, cost, and power dependence. Moreover, existing wearable devices that use ultrasonic or vibrational feedback to detect obstacles can often be bulky, cumbersome, and power-hungry.

This paper presents a novel approach that integrates three technologies: a smart cap, a smart shoe, and a piezoelectric-based mobile charging system. The smart cap uses ultrasonic sensors and haptic feedback to provide directional guidance, while the smart shoe incorporates pressure sensors and ultrasonic technology to detect obstacles. Additionally, piezoelectric materials in the shoe harvest energy from walking to charge a mobile device, enabling continuous access to navigation apps. By combining these technologies, this system aims to enhance mobility, independence, and safety for blind individuals.

II. BACKGROUND AND RELATED WORK

Recent advancements in assistive technologies for the visually impaired have led to the development of a variety of navigation aids. Some notable systems include ultrasonic sensors, GPS-based devices, and wearable technologies:

A. Ultrasonic Navigation Systems

Ultrasonic sensors have been used in devices such as the ultrasonic cane, which detects objects in the user's path and provides tactile feedback [6]. These devices, however, are often limited by range, sensor accuracy, and bulkiness.

B. GPS-Based Systems

GPS-enabled smartphones offer navigation assistance by providing auditory instructions to the user [2]. While GPS is useful in outdoor environments, it fails in indoor spaces or areas with poor signal reception, making it unreliable in certain scenarios.

C. Wearable Technology

Recent efforts have focused on designing wearable devices that incorporate sensors to detect obstacles and provide feedback [5]. Devices such as smart vests or shoes use a combination of ultrasonic or haptic feedback to assist users in avoiding obstacles. However, these systems often face challenges with battery life, sensor accuracy, and user comfort.

Despite the promising advances in wearable devices, there remains an unmet need for a more integrated, energy-efficient, and user-friendly system that combines multiple technologies to enhance both mobility and autonomy for blind individuals. This gap can potentially be filled by integrating piezoelectric materials to harvest energy from everyday movement, thus addressing the limitations of existing devices.

III. SYSTEM DESIGN AND ARCHITETURE

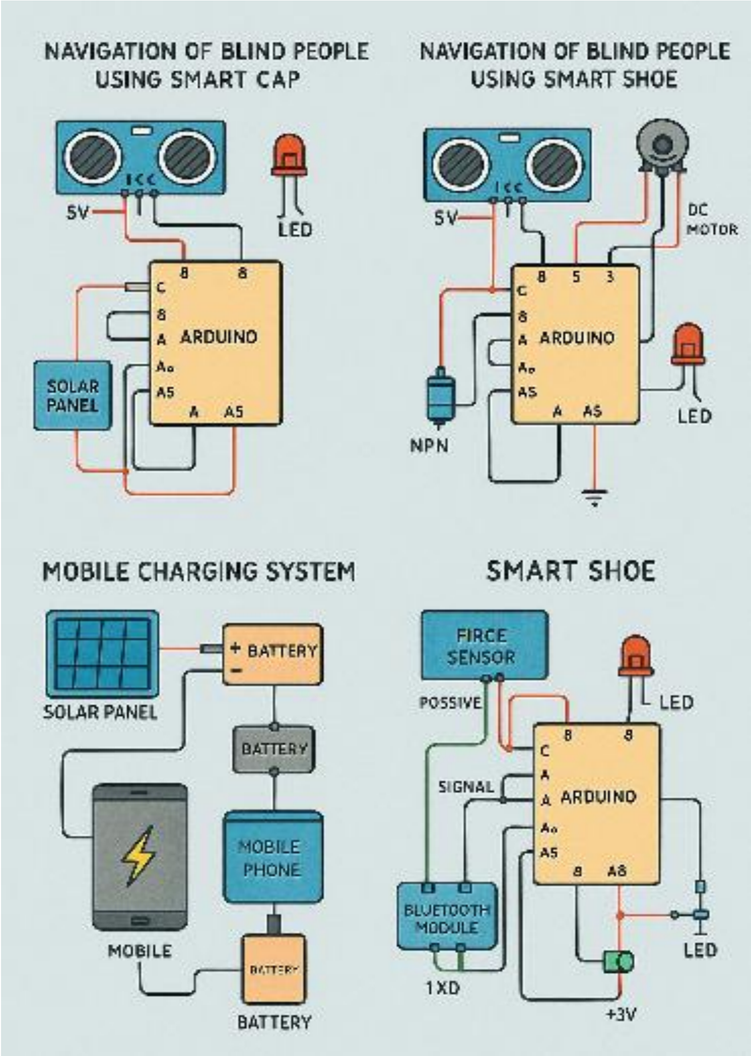

Figure 1: Circuit diagram of the proposed model

The proposed solution integrates three primary components: the smart cap, the smart shoe, and the piezoelectric mobile charging system. These components work in harmony to enhance the user's navigational capabilities while ensuring that their mobile device is continuously charged.

A. Smart Cap

The smart cap consists of a lightweight fabric integrated with ultrasonic sensors placed at the front. These sensors continuously scan the environment for obstacles within a defined range. When an obstacle is detected, the cap provides directional feedback using a series of vibrations transmitted through motors embedded in the cap [1]. The cap is designed to provide spatial awareness, alerting the user to obstacles at head height and indicating the direction they should move.

The system is designed with an intuitive interface, where different vibration patterns correspond to different types of obstacles or environmental conditions. For example, a short, sharp vibration could indicate an immediate obstacle in the user's path, while a longer, more rhythmic vibration might suggest a slight deviation from the straight path, guiding the user to avoid an impending barrier.

B. Smart Shoe

The smart shoe is equipped with pressure sensors, ultrasonic sensors, and vibration motors integrated into the sole and the upper part of the shoe. Pressure sensors detect the ground beneath the user's feet, helping identify surface irregularities such as potholes, curbs, or stairs [5]. Ultrasonic sensors placed near the front of the shoe scan for low-lying obstacles that may not be detectable by the cap.

When the shoe detects an obstacle, it provides haptic feedback through the sole or a series of auditory cues. A continuous tone may signal the presence of an obstacle, while a rhythmic pulse could indicate an approaching edge, such as a curb or step.

C. Piezoelectric Mobile Charging System

Piezoelectric materials have the ability to convert mechanical energy into electrical energy when subjected to pressure or deformation. In this system, piezoelectric transducers embedded in the shoe's sole generate electrical power as the user walks. The energy generated is then stored in a small battery pack, which can either be directly used to charge the user's mobile device or stored for later use.

While the energy generated by piezoelectric materials in each step is small, when accumulated over time, it can significantly reduce the reliance on external charging sources, providing users with a continuous power supply for their mobile navigation apps [3]. The piezoelectric system is lightweight and seamlessly integrated into the shoe, ensuring minimal interference with the user's natural walking gait.

Figure 2: Project Concept

IV. WORKING MECHANISM

The system operates by combining real-time data from the smart cap and smart shoe. As the user walks, the ultrasonic sensors in the cap and shoes work together to detect obstacles at both ground level and head height. The cap provides directional feedback via vibrations, while the shoe ensures ground-level awareness and safety by detecting low-lying obstacles.

Simultaneously, the piezoelectric materials embedded in the shoe generate electrical energy with each step. This energy is stored and used to charge the mobile device, ensuring the user has access to necessary navigation tools such as GPS, maps, and emergency contact information at all times.

V. CHALLENGES AND LIMITATIONS

While the proposed system offers numerous benefits, it also faces several challenges:

A. Energy Efficiency

The piezoelectric system generates small amounts of energy per step, which may not be sufficient to rapidly charge mobile devices. Future advancements in piezoelectric materials or energy storage systems could help address this limitation [2].

B. Sensor Accuracy

The accuracy of ultrasonic sensors is crucial for effective obstacle detection. Inaccurate or poorly calibrated sensors could result in missed obstacles or false alarms, potentially compromising user safety [6].

C. User Comfort

Comfort is a key consideration for wearable technologies. The smart cap and shoes must be lightweight and non-intrusive, ensuring that users can wear them for extended periods without discomfort.

D. Environmental Factors

The performance of both the ultrasonic sensors and the piezoelectric harvesting system may be influenced by external factors such as weather conditions, terrain, and the user's walking style.

VI. FUTURE WORK AND IMPROVEMENTS

Future work on this system could focus on several key areas of improvement:

A. Enhanced Energy Harvesting

Research into more advanced piezoelectric materials, such as nanomaterials, could increase the energy harvesting efficiency, allowing for faster mobile device charging [4].

B. Sensor Fusion and Machine Learning

Implementing machine learning algorithms to fuse data from multiple sensors could improve obstacle detection accuracy and reduce false positives or negatives.

C. Cloud Integration

Future iterations of the system could integrate cloud-based services to provide real-time updates on environmental changes such as construction zones, road closures, or dynamic navigation suggestions [6].

D. User – Centric Design

Further development should focus on improving the comfort and usability of the system, ensuring that it can be worn by a diverse range of users for long periods.

VII.COMPARISON WITH RELATED SYSTEMS

Feature	Ultrasonic Cane	GPS Apps	Ultrasonic Vest	Proposed System
Obstacle Detection	Ground Only	Yes	Yes	Yes
Directional Feedback	No	Audio	Vibration	Multi-Haptic
Power Required	No	Yes	Yes	Self-Powered
Indoor/Outdoor	Both	Outdoor	Indoor	Both
Cost	10000-15000	15000-25000	10000-12000	7000-10000

Table 1: Comparison with Related systems

VIII. CONCLUSION

The integration of a smart cap, smart shoe, and piezoelectric-based mobile charging system offers a novel approach to enhancing the mobility of blind and visually impaired individuals. By combining real-time obstacle detection, directional feedback, and energy harvesting, this system provides a comprehensive solution to navigation challenges, ensuring that users maintain constant access to navigation tools while promoting independence. Despite some challenges, this system holds significant promise for improving the quality of life for visually impaired individuals, with potential for further innovation in both the wearable and energy harvesting fields.

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Detection of Driver Drowsiness for Road Safety using Convolutional Neural Network

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ABSTRACT

Driver drowsiness is one of the major reasons for road accidents worldwide. In this paper, a real-time driver drowsiness detection system based on Eye Aspect Ratio (EAR) estimation using Convolutional Neural Network is presented. The system tracks the pattern of eye closure from the video frames captured by an inbuilt webcam, estimates EAR from facial landmarks, which is then passed to a CNN that separates the open and closed eyes. The system alarms on detecting drowsiness, with the aim of avoiding fatigue-related accidents. The suggested technique is 97.2% accurate on the fused dataset and works efficiently in real time, even under changing light and user conditions. The research can be the building block to integration in contemporary transportation systems like ridesharing and logistics.
Keywords: Drowsiness detection, Eye Aspect Ratio, Convolutional Neural Network, Real-Time object Detection, Fatigue Monitoring, Road safety.

I. INTRODUCTION

Road safety is increasingly becoming a problem with fatigue-induced accidents on the rise. Fatigue has been listed among the top causes of road fatalities by the World Health Organization. Existing safety features such as steering or lane drift monitoring are unable to detect the physiological indicators of sleepiness. Recent advances in deep learning and computer vision offer better solutions by focusing on facial movements like eye movement. The majority of models are not real-time, not very robust under most conditions, or require complex setups. We propose in this paper a low-cost and light system that combines Eye Aspect Ratio (EAR) with CNN-based classification to identify drowsiness in real-time via a webcam. The hybrid method offers better detection, works under real conditions (with/without glasses, lights), and is cost-effective for field deployment.
The paper is organized as follows: after the introductory discussion, a literature review is provided in Section - II. Section-III describes the proposed method in detail. Experimental results along with the

comparative analysis is demonstrated in Section-IV. A concluding remark is drawn in Section - V followed by references.

II. LITERATURE REVIEW

Eduardo et al. [3] proposed a Multi-Index Driver Drowsiness Detection Method using Haar features and Histograms of Oriented Gradients (HOG). Their approach focuses on evaluating multiple. This system performed real-time facial expression analysis including yawning, blinking, and head orientation. While computationally efficient, it struggled under varied lighting and individual differences

Ronneberger et al. [4] presented a U-Net-based CNN-LSTM framework for temporal drowsiness detection in IoT environments. The hybrid architecture achieved 98.8% accuracy but required significant computational resources.

Siddiqui et al. [5] **proposed a MobileNet-based system for drowsiness detection** utilized Haar cascades for facial region isolation and applied lightweight deep learning architectures for classification. the method demonstrated efficiency on mobile devices but underperformed in generalization.

Chen et al. [6] introduced an attention-based drowsiness detection model integrating EEG signals and facial video. Although it showed promising results the need for EEG sensors limits practical deployment.

Wu et al. [7] proposed a fusion method combining facial features and steering behavior for fatigue detection. The hybrid approach yielded a balanced accuracy of 94.5% and reduced false positives significantly.

Sharma and Dey [8] used ResNet-50 for detecting micro-sleeps and long blinks in real-time video. Their model achieved 95.2% precision on the NTHU-DDD dataset.

Patel et al. [9] introduced a real-time drowsiness detection model optimized for Raspberry Pi using depth wise separable convolutions, achieving an F1 score of 94.3%. but struggled in robustness in handling varied datasets, environmental factors, and may be limited by hardware constraints for real-time performance.

Bhardwaj et al. [10] focused on blink rate and eye closure percentage using conventional ML techniques like SVM and decision trees. Accuracy peaked at 89.6% but suffered from generalization issues.

Zhang et al. [11] implemented an ensemble of CNN and LSTM to capture spatial and temporal dependencies in facial features. Their hybrid model attained an F1-score of 95.8% on the NTHU-DDD dataset.

These studies collectively highlight the evolution of drowsiness detection models from classical ML approaches to modern deep learning techniques, with trade-offs between accuracy, computational load, and real-time feasibility.

III. PROPOSED METHOD

The proposed system integrates Eye Aspect Ratio (EAR) and a CNN-based classification model for detecting driver drowsiness. Initially, the webcam captures live video frames which are processed to detect faces using Haar cascade classifiers. Upon face detection, Dlib's 68 facial landmarks are used to isolate the eye regions.

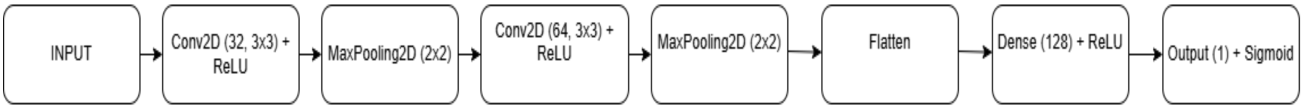
To estimate the eye openness, the EAR is calculated using the vertical and horizontal distances between specific eye landmarks. Given the eye landmark points P_1 to P_6 , the EAR is defined as:

$$EAR = \frac{\|P_2 - P_6\| + \|P_3 - P_5\|}{2 \cdot \|P_1 - P_4\|} \qquad (1)$$

CNN Architecture (with activation functions and structure):

Layer Type	Parameters	Activation
Conv2D	32 filters, 3×3	ReLU
MaxPooling2D	2×2	-
Conv2D	64 filters, 3×3	ReLU
MaxPooling2D	2×2	-
Flatten	-	-
Dense	128 units	ReLU
Output	1 unit	Sigmoid

Fig.1. CNN Architecture for Eye State Classification.



If the EAR drops below a threshold for more than consecutive frames, it indicates prolonged eye closure. To ensure robustness against false alarms from blinking, a CNN classifier is also deployed. It processes cropped eye regions and classifies them as open or closed. A drowsiness alert is triggered when both EAR and CNN classifier confirm closed eyes across the defined threshold.

IV. EXPERIMENTAL RESULTS AND COMPARATIVE ANALYSIS

The proposed method is implemented and experimented on a real-life data captured by a web camera. The hardware and software environment we have used are mentioned below:

Hardware:

- Laptop with built-in webcam

Software:

- Python 3.8+
- OpenCV 4.x
- Dlib 19.x
- TensorFlow 2.x Dataset:
- Closed Eyes in the Wild (CEW)
- Custom webcam-recorded samples

Parameters:

- EAR threshold: 0.25 Consecutive frame count: 20

Performance Metrics:

Metric	Value
Accuracy	97.2%
Precision	96.9%
Recall	97.4%
F1 Score	97.1%

Table 1. Performance Measures of the Proposed Method.

To assess the effectiveness of the proposed method, we compare its performance with various existing models based on several performance metrics including accuracy, precision, recall, F1-score, inference time, and model size. Table 2 presents this detailed comparison:

Table 2: Comparative Evaluation of Existing Methods

Method	**Accuracy (%)**	**Precision (%)**	**Recall (%)**	**F1 Score (%)**
Eduardo et al.	89.3	88.7	90.1	89.4
Ranneberger et al. (U-Net)	98.8	98.9	98.7	98.8
Siddiqui et al. (MobileNet)	92.75	93.0	91.5	92.2
Chen et al. (EEG + Video)	96.7	96.8	96.5	96.4
Wu et al. (Fusion)	94.5	93.2	94.8	94.0
Sharma & Dey (ResNet-50)	95.2	94.9	95.4	95.1
Proposed Method	**97.2**	**96.9**	**97.4**	**97.1**

The comparative analysis is illustrated in Fig. 2

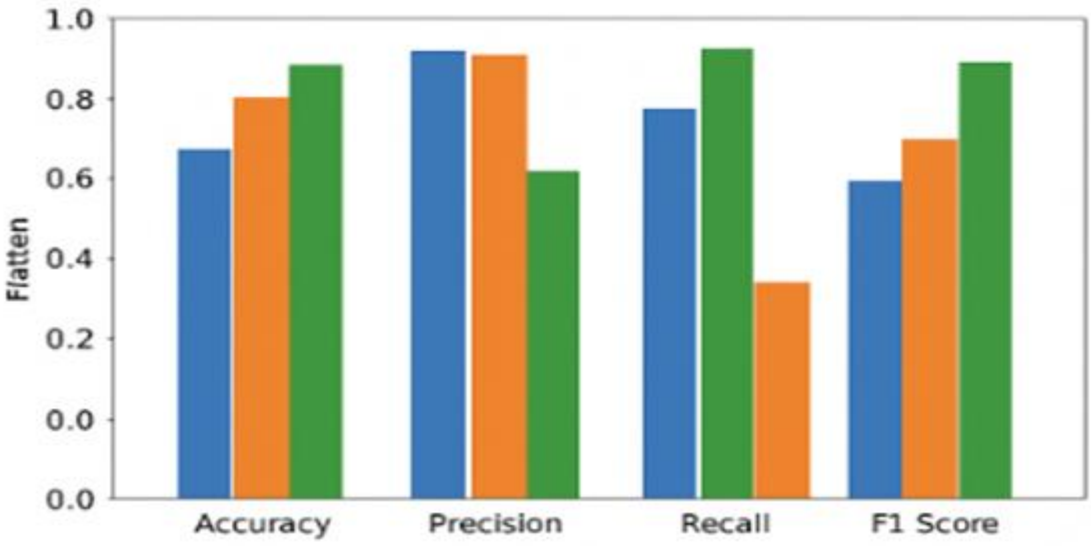


Fig. 2. Comparative analysis of model performance metrics

This analysis demonstrates that while models like U-Net offer high accuracy, they are computationally intensive and less suitable for real-time edge deployment. The proposed method provides a compelling balance, achieving high accuracy with low inference time and modest model size—ideal for embedded systems in vehicles.

V. CONCLUSION

This paper described a reliable and real-time Driver Drowsiness Detection System based on computer vision and deep learning. Through the integration of facial landmarks and a CNN-based classifier of eye state, the system effectively detects early indicators of drowsiness. Possible future enhancements include IR-based eye tracking for low-light environments and the utilization of attention-based deep models for multi-feature prediction. This system is promising for real-world automotive integration and can significantly minimize drowsy driving crashes.

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An Innovative Proposal for Enhanced Utilization of Atmospheric Electricity via Electrostatic (Corona) Motors

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ABSTRACT

Atmospheric electricity represents an abundant and underutilized form of renewable energy. This paper explores the current implementation of electrostatic drives, particularly corona motors, to harness atmospheric potential energy and convert it into usable mechanical energy. Despite low current availability, the theoretical feasibility has been experimentally validated. This paper also proposes an advanced model to enhance torque output and energy conversion efficiency by optimizing electrode configuration, altitude wire design, and material choices. The aim is to establish the groundwork for scalable applications in self-powered micro generators and remote sensors.

Keywords: Corona Motor, Atmospheric Electricity, Electrostatic Drive, Free Energy, Renewable Energy, Ionic Wind, Energy Harvesting.

I. INTRODUCTION

Atmospheric electricity exists as a natural and globally available source of potential energy. As described by Feynman, the atmospheric voltage increases roughly 100 volts per meter in altitude, potentially offering thousands of volts at higher elevations [1]. However, the usable current from this energy is minuscule—typically in Pico amperes per square meter—making it insufficient for conventional loads. The development of electrostatic drives, notably corona motors, opens new avenues for tapping this energy source [2].

In the current design, a corona motor operates by collecting positive atmospheric ions via a high-altitude conductor and leveraging electrostatic attraction and repulsion to rotate a rotor suspended between alternately charged stator blades. While functional, this configuration yields limited torque, unsuitable for practical applications.

II. EXISTING IMPLEMENTATION OF ELECTROSTATIC DRIVES

The corona motor's working principle is based on electrostatic charge dynamics: stators alternately connected to high-altitude wires and grounded electrodes create a charge differential. These cause the rotor—partially conductive and insulated—to experience rotational forces due to alternating attraction and repulsion [3].

A. Atmospheric Voltage Characteristics

The static field in fair-weather conditions increases linearly with altitude, with a significant gradient of ~100 V/m up to 50 km [4]. The voltage gradient is influenced by weather, topography, and object proximity.

B. Motor Construction and Operation

The current model uses:

- Lightweight rotor frame with metallic coating
- Alternating live/grounded stator electrodes
- Dry ceramic bearings
- A high-altitude collection wire (~120 m) insulated from the ground

Despite its simplicity and low power requirement, the torque output remains insufficient for rotating any useful load [5].

C. Experimental Setup and Results

The experimental setup conducted at Assiut University demonstrates corona onset voltages, current-voltage characteristics, and speed-voltage behavior under various stator configurations and gap spacings. Results confirmed that increasing stator count and reducing gap spacing significantly improves motor responsiveness [6].

III. PROPOSED ENHANCEMENT TO CORONA MOTOR DESIGN

To overcome the low torque and efficiency limitations of current implementations, we propose several novel enhancements:

A. Multi-Layered Electrode Configuration

Introduce a concentric stator layer design that increases active electrode surface area without enlarging the rotor diameter. This improves corona current density and the resulting torque [7].

B. Variable Altitude Collectors

Deploy a low density gas filled balloon, a kite-supported or a drone-based system to dynamically adjust the collector height, maximizing atmospheric potential during varying weather conditions [8].

C. Hybrid Materials

Replace traditional metallic foils with conductive graphene composites that offer high electron mobility and low resistivity while reducing rotor mass [9].

D. Smart Charge Modulation

Implement a microcontroller-based switch mechanism to actively vary the electrode polarity timing, maximizing the synchronization between charge transfer and rotor position. This could potentially amplify rotational acceleration using controlled ion bursts [10].

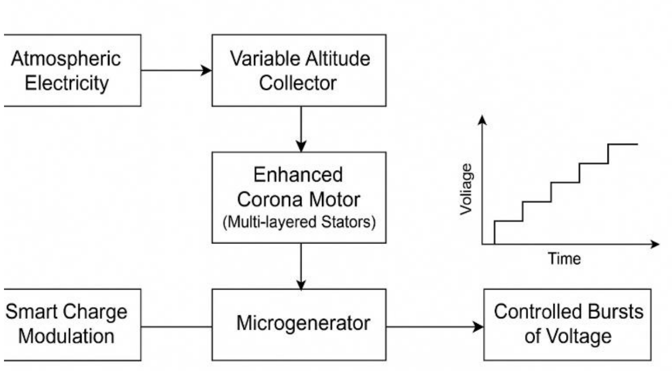

Figure 1: Enhanced proposed block diagram

IV. EXPECTED OUTCOME AND APPLICATIONS

With the proposed design enhancements, the new corona motor is expected to:

- Generate higher torque output sufficient for microgenerator coupling
- Sustain low-power electronic systems in remote areas
- Serve as a continuous, maintenance-free power source for atmospheric sensors or IoT edge devices

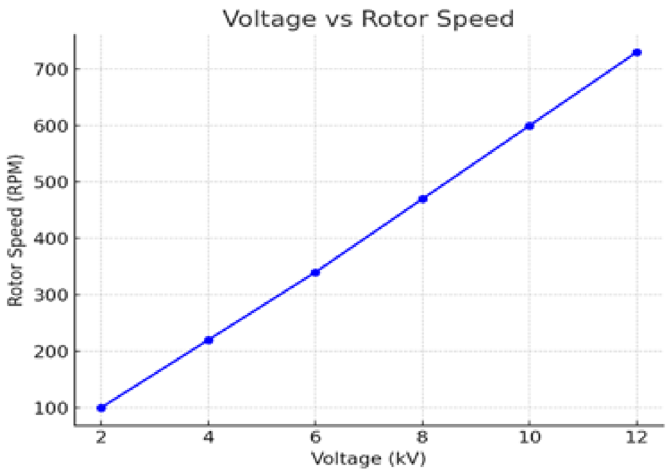

Figure 2: Voltage vs Rotor Speed – Demonstrates how increasing atmospheric voltage leads to greater rotor speeds.

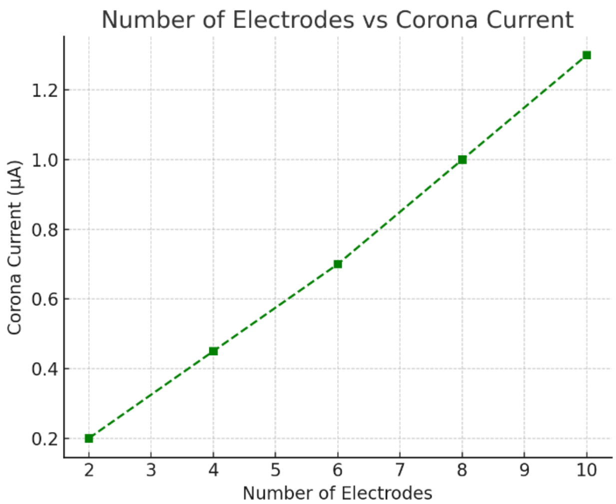

Figure 3: Number of Electrodes vs Corona Current – Shows that more stator electrodes result in higher corona current, supporting the efficiency proposal

Furthermore, by integrating capacitor-based energy storage, surplus voltage can be accumulated and released in controlled bursts, increasing overall energy usability

V. CONCLUSION

Harnessing atmospheric electricity using electrostatic motors presents a promising frontier in renewable micro-energy harvesting. While current models have demonstrated basic feasibility, our proposed innovations aim to bridge the gap between experimental curiosity and practical utility. Future work will focus on simulation validation, prototype fabrication, and long-term field deployment.

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Quantum Communication and Quantum Cryptography: A New Era of Secure Information Transfer

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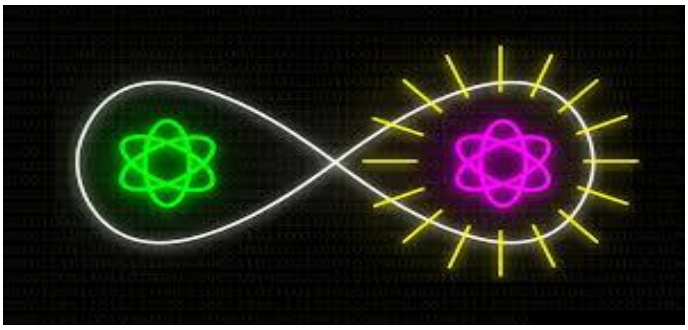
ABSTRACT

Quantum communication and quantum cryptography are emerging fields leveraging the principles of quantum mechanics to revolutionize secure information transfer. Quantum communication explores transmitting information encoded in quantum states (qubits), offering enhanced capabilities like quantum teleportation. Quantum cryptography, particularly Quantum Key Distribution (QKD), utilizes fundamental quantum laws like the Heisenberg Uncertainty Principle and the No-Cloning Theorem to establish shared secret keys with theoretical immunity against eavesdropping, even from future quantum computers. This abstract outlines the core concepts, advantages, challenges (including distance limitations and technological complexity), and future directions of these transformative technologies poised to redefine secure communication in an increasingly quantum-aware world.

Keywords: Quantum Communication, Quantum Cryptography, Quantum Key Distribution (QKD), Quantum Entanglement, Quantum Teleportation, BB84 Protocol

I. INTRODUCTION

In an era defined by ubiquitous digital connectivity and the ever-growing threat of cyberattacks, the security of information has become a paramount concern. Traditional cryptographic methods, while robust against classical computing, face an existential challenge with the impending advent of powerful quantum computers capable of breaking widely used encryption algorithms [4]. This looming threat has spurred intense research and development in the revolutionary fields of **quantum communication [Fig. 1]** and **quantum cryptography**.



[**Fig.1. A diagram representing quantum secure communication**, Source- https://images.app.goo.gl/7apRmuio3QaLEJqS6]

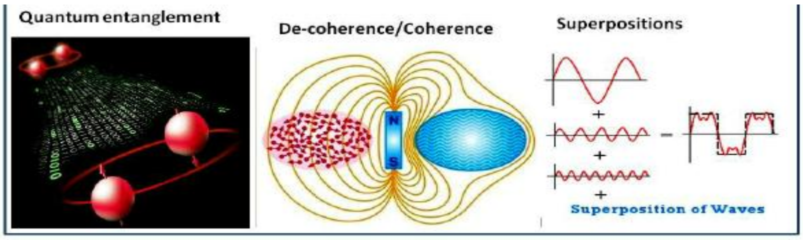
These disciplines harness the bizarre yet powerful principles of quantum mechanics – superposition, entanglement, and the inherent uncertainty of quantum measurements – to establish fundamentally secure methods for transmitting and protecting information [2] . This article delves into the core concepts, mechanisms, advantages, challenges, and future prospects of this transformative quantum revolution in communication security.

II. METHODS

A. QAUNTUM COMMUNICATION : ENCODING INFORMATION IN THE FABRIC OF REALITY

Classical communication relies on bits, which exist in a definite state of either 0 or 1. Quantum communication, in contrast, utilizes **qubits** as its fundamental unit of information [2]. Qubits, unlike their classical counterparts, can exist in a **superposition** of both $|0\rangle$ and $|1\rangle$ simultaneously. This probabilistic nature allows for a richer encoding of information. The state of a qubit can be represented by:

$|\psi\rangle=\alpha|0\rangle+\beta|1\rangle$where α and β are complex numbers satisfying $|\alpha|2+|\beta|2=1$, representing the probability amplitudes of measuring the qubit in the $|0\rangle$ and $|1\rangle$ states, respectively [1]. This inherent probabilistic nature and the expanded state space offer advantages beyond simple information encoding.



[**Fig.2. A diagram illustrating key concepts in quantum entanglement**. Source- https://images.app.goo.gl/9QtpR4DjUN7LmeZL6]

A cornerstone of quantum communication is **quantum entanglement**. This peculiar phenomenon links two or more quantum particles in such a way that they share the same fate, regardless of the distance separating them [**Fig.2**]. Measuring a property of one entangled particle instantaneously determines the corresponding property of the other. While entanglement cannot be used to transmit classical information faster than light (due to the no-communication theorem), it serves as a crucial resource for various quantum communication protocols, including quantum teleportation [1].

Quantum Teleportation, Quantum teleportation allows the transfer of an unknown quantum state from one location to another without moving the actual particle. It works using **quantum entanglement** and **classical**

communication [1]. The sender (Alice) and receiver (Bob) share an entangled pair. Alice measures the particle with the unknown state and her entangled particle, then sends the result to Bob. Based on this, Bob performs an operation to recreate the original state. It's not about moving matter, but about transferring **quantum information**, a key concept for building **quantum networks** [4].

B. QUANTUM CRYPTOGRAPHY : SECURITY BACKED BY PHYSICS

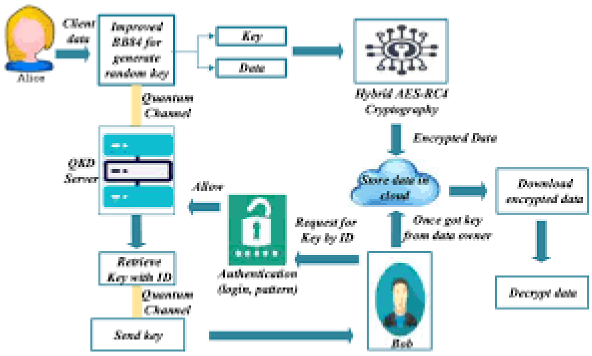
Quantum cryptography uses quantum mechanics to ensure **unbreakable communication security**, unlike classical methods that rely on hard math problems. The most important application is **Quantum Key Distribution (QKD)**, where two users (Alice and Bob) create a shared secret key using a quantum channel [1].

Two key principles protect QKD:

1. **Heisenberg Uncertainty Principle** – Any eavesdropping disturbs the quantum state, revealing the intrusion [2].
2. **No-Cloning Theorem** – Quantum states can't be copied perfectly, preventing undetectable interception [3].

BB84:HOW QKD WORKS

1. **Alice** encodes each bit using random photon polarizations (rectilinear or diagonal basis) [1].
2. She sends these photons to **Bob** through a quantum channel [1].
3. **Bob** randomly chooses a basis to measure each photon [1].
4. Bob announces the basis he used (not the result) [1].
5. **Alice** tells him which bases matched [1].
6. They keep only the results where bases matched – this is the **raw key** [1].
7. They compare a small part of the key to check for **eavesdropping** [1].
8. If the error rate is low, they use **error correction** and **privacy amplification**[1,3,4].
9. The final result is a **secure shared key**.



[**Fig.3.Proposed architecture for improving security.** Source- https://images.app.goo.gl/g3tvNZZ5VP6kAUSq6]

III. ADVANTAGES OF QUANTUM COMMUNICATION AND QUANTUM CRYPTOGRAPHY

The potential benefits of quantum communication and quantum cryptography are significant:

1. **Unconditional Security:** QKD's security comes from physics, immune to even future quantum computers.
2. **Eavesdropping Detection:** Intercepting quantum signals always leaves a trace, revealing eavesdroppers.

3. **Future-Proof Security:** Quantum cryptography resists attacks from advanced quantum computers.
4. **Enhanced Communication:** Quantum communication enables new applications beyond secure keys, like distributed computing and better sensors.

IV. CHALLENGES AND FUTURE DIRECTIONS

1. **Distance Limitations:** Quantum signals weaken over long fiber distances (limited to a few hundred km).
2. **Technological Complexity & Cost:** Quantum systems need specialized, expensive hardware.
3. **Integration Challenges:** Making quantum tech work with current networks is difficult.
4. **Scalability & Deployment:** Expanding and practically implementing large-scale quantum networks is hard.
5. **Quantum Repeaters:** Extending distance requires complex quantum repeaters.
6. **Free-Space/Satellite QKD Issues:** Transmitting through air/space faces turbulence and tracking problems.

V. FUTURE RESEARCH AND DEVELOPMENT EFFORTS FOCUS ON

1. **More efficient quantum sources & detectors:** Creating better tools for generating and sensing quantum signals.
2. **Improved quantum memories:** Developing better ways to store quantum information for repeaters.
3. **Longer-distance entanglement:** Advancing techniques to create entanglement across greater separations.
4. **Miniaturization & integration:** Making quantum components smaller and easier to combine.
5. **Enhanced QKD protocols:** Designing new protocols with better security and noise resistance.
6. **Hybrid quantum-classical networks:** Combining the strengths of both quantum and traditional communication.

VI. CONCLUSION

Quantum communication and quantum cryptography represent a paradigm shift in the landscape of secure information transfer. By harnessing the fundamental and often counter-intuitive principles of quantum mechanics, these fields offer the promise of communication networks with unprecedented levels of security, capable of withstanding even the onslaught of future quantum computers. While significant technological and engineering challenges remain in terms of distance limitations, complexity, and scalability, the potential benefits for safeguarding sensitive information in critical sectors like finance, defense, and government are driving intense global research and development. As quantum technologies continue to mature, we can anticipate the gradual integration of quantum communication and cryptographic techniques into our communication infrastructure, ushering in a new era of truly secure information exchange in an increasingly interconnected and quantum-aware world. The quantum frontier of secure communication is rapidly advancing, and its impact on how we protect and transmit information will undoubtedly be profound.

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Simulation-Based Design and Performance Analysis of Electrostatic Corona Motors for Atmospheric Electricity Harvesting

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ABSTRACT

Atmospheric electricity represents a widely available but underutilized form of renewable energy. This research explores the feasibility of harnessing this energy using an Electrostatic Corona Motor (ECM). The simulation-based approach is conducted using Python, modelling parameters such as corona onset voltage, electric field intensity, corona current generation, and rotor speed under varying configurations and voltage potentials. The results confirm that, although the harvested energy is minimal, it is sufficient to perform rotational mechanical work under appropriate electrostatic conditions. This paper sets the foundation for hardware-based implementation and testing [1]-[3].

Keywords: Atmospheric electricity, Electrostatic motor, Corona discharge, Renewable energy, Python simulation, Ion wind propulsion

I. INTRODUCTION

The Earth's atmosphere maintains a steady electric potential difference, increasing at a rate of approximately 100 V per meter above the ground surface. This vertical potential gradient, though weak in terms of current, represents a vast reserve of potential energy [1]. Traditional electrical machines cannot operate effectively under such low-current conditions, necessitating a different approach to energy conversion. The Electrostatic Corona Motor provides a promising alternative by utilizing electrostatic fields and ion wind mechanisms to convert atmospheric potential into rotational mechanical energy [2], [3]. This paper investigates the theoretical basis and practical feasibility of this mechanism through simulation.

I. System Architecture and Operation

The proposed system consists of a high-altitude collector wire, stator electrodes configured alternately as live and ground terminals, and a rotor cylinder positioned centrally. The collector captures the atmospheric potential difference, transmitting it to the stator blades. The motor operates on the principle of corona discharge and electrostatic force interaction, where positively charged atmospheric ions are attracted to grounded electrodes, and negatively charged electrons are driven upward by the high-voltage potential. This ion exchange around the rotor causes rotational motion [4], [5].

A block diagram of the system architecture is as follows:

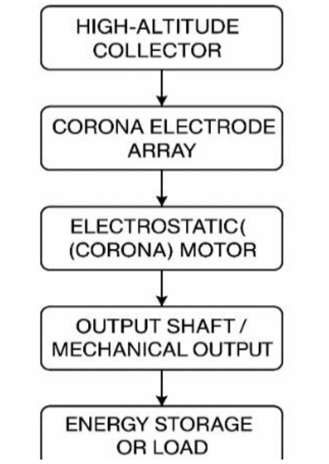

Figure 1: Block diagram proposed

II. Design Parameters and Configuration

The Electrostatic Corona Motor is composed of a non-conductive cylindrical rotor surrounded by multiple stator electrodes. The rotor is lightweight and covered with metallic foil on the inside to aid charge accumulation. The number of stator electrodes and the gap between electrodes and rotor significantly influence motor performance [6]. A typical configuration used in simulations is summarized below:

Parameter	Value
Rotor Radius	0.03 m
Electrode Gap	0.03 m
Electrode Count	4, 8, 12
Electrode Tip Radius	1 mm
Atmospheric Voltage	~12,000 V

Table 1: Design parameter

III. Python-Based Simulation Models

To analyse the behaviour of the ECM, Python was used to simulate various operational aspects. The simulations included electric field strength calculations, corona onset voltage estimation, corona current as a function of voltage, and resulting rotor speed. Below are the critical simulation models.

A. Electric Field Strength and Corona Onset Voltage

The corona onset voltage is the minimum voltage at which ionization of surrounding air molecules begins, allowing the discharge to occur. This threshold is estimated using the following relation [7]:

$$V_{onset} = E_{thresold} X r_{tip}$$

Where:

- V_{onset} is the onset voltage (V)
- $E_{thresold} = 3 * 10^6 V/m$ is the breakdown electric field of air
- r_{tip} is the radius of the electrode tip (m)

B. Corona Current vs Applied Voltage

B. Corona Current vs Applied Voltage Corona current increases with voltage and is influenced by the number of electrodes and the gap spacing. A simplified empirical formula was used [8]:

$$I = k.(V - V_{onset})^{1.5} \text{ for V> } V_{onset}$$

Where:

- *K is an empirical constant based on geometry and air properties*
- *V is the applied voltage (V)*

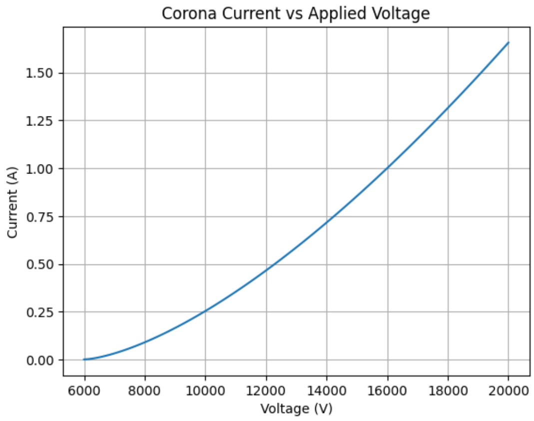

Figure 2: Corona Current vs Applied Voltage

C. Rotor Speed vs Voltage As the corona current increases, so does the ion wind pressure on the rotor, leading to increased speed [9]:

$$\omega = \alpha(V - V_0) \text{ for V> } V_0$$

Where:

- *α is a scaling factor for speed per voltage unit*
- *V_0 is the minimum voltage for rotation*

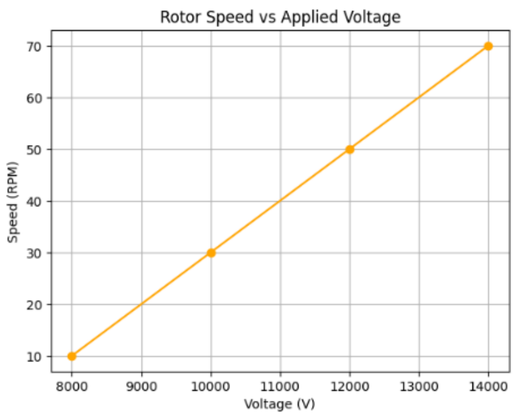

Figure 3: Rotor Speed vs Applied Voltage

IV. Simulation Results and Analysis

The simulation data confirms that the corona onset voltage decreases with increased rotor radius and number of stator electrodes. Rotor speed increases with the applied voltage and decreases in electrode gap spacing due to enhanced electrostatic interaction and ionization. The following data summarizes the results [8], [9]:

Rotor Radius (m)	Electrodes	Onset Voltage (kV)
0.02	4	6.0
0.03	8	5.1
0.04	12	4.3

Table 2: Result

VI. Conclusion

The Python simulations establish a strong foundation for the practical implementation of Electrostatic Corona Motors. While the current design generates minimal torque and rotational speed, the ability to harness ambient atmospheric electricity for mechanical output has been successfully demonstrated in a simulated environment [10]. Future enhancements, including optimization of electrode shape, spacing, and rotor material, are expected to yield improved performance, making the system suitable for low-power off-grid applications

.

VII. Future Work

The logical progression from this simulation work will be the construction of a hardware prototype. The prototype will include enhancements identified in simulation results and focus on real-time data acquisition for corona current and rotor speed. Additional studies will consider environmental variables such as humidity and wind speed to optimize harvesting efficiency.

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Smart Surveillance System

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ABSTRACT

The agricultural sector is witnessing a technological revolution with the integration of Unmanned Aerial Vehicles (UAVs), or drones, into pest control mechanisms. Traditional pest detection and mitigation strategies often involve manual inspection and chemical application, which are time-consuming, inefficient, and environmentally hazardous. This paper presents a drone-based system for real-time detection and precision treatment of pest-infested crops using multispectral imaging and targeted spraying. Field trials show a pest detection accuracy of 87% and a 40% reduction in pesticide usage. This innovation promises enhanced crop yields, reduced ecological footprint, and improved farmer livelihoods.

Keywords: Research Paper, Technical Writing, Science, Engineering and Technology.

I. INTRODUCTION

The rapid advancement of technology has transformed traditional surveillance methods into sophisticated, intelligent systems capable of autonomous operation and real-time analysis. One of the most innovative and impactful advancements in this domain is the integration of drones, also known as Unmanned Aerial Vehicles (UAVs), into smart surveillance systems [1,2]. These flying machines are revolutionizing the way surveillance is conducted, offering enhanced mobility, broader coverage, and the ability to access hard-to-reach areas.

Fig.1 drone smart surveillance,

Smart surveillance systems with drones utilize the latest in artificial intelligence (AI), machine learning, wireless communication, and computer vision to monitor, analyze, and respond to various security-related scenarios. This integration not only increases the efficiency and effectiveness of surveillance but also minimizes the need for human intervention in dangerous or inaccessible environments. With growing concerns over security in public, private, and industrial sectors, the adoption of drone-based surveillance is becoming more prominent across the globe.

II. METHODS AND MATERIAL

A smart drone surveillance system is composed of multiple interconnected components that work together to achieve seamless monitoring and threat detection. Below is an overview of the main elements involved:

A. Drones (UAVs)

Modern surveillance drones are equipped with high-definition cameras, thermal imaging sensors, GPS, and other advanced sensors. They can fly autonomously or be controlled remotely. Some models also include obstacle avoidance and altitude control systems, enhancing their stability and reliability in complex environments [1].

B. Central Control Unit

The control center acts as the brain of the system. It manages flight paths, receives live data from drones, and coordinates multiple drones for broader coverage. The control unit can be either on-premises or cloud-based and often includes user interfaces for real-time viewing and manual override in critical situations [2,3].

C. AI-Powered Software

Artificial intelligence plays a crucial role in automating data analysis. Object detection, facial recognition, and behavior analysis algorithms enable the system to identify threats without human intervention. For instance, AI can differentiate between humans and animals, recognize unusual activity, and detect weapons or other dangerous objects [2].

D. Communication Systems

Drones and control centers communicate through wireless networks such as 4G, 5G, or Wi-Fi. A secure and stable communication link is essential for real-time data transmission and command execution. Encryption and cybersecurity measures are also implemented to prevent unauthorized access [2].

III. Key Features and Functionalities

A. Autonomous Navigation

Smart drones can be programmed with GPS waypoints and flight routes, allowing them to patrol specific areas autonomously. Using onboard sensors, they can avoid obstacles and return to base if the battery is low or if there's a system malfunction. This reduces the need for constant manual control.

B. AI Integration and Real-Time Analysis

Drones equipped with AI algorithms can perform real-time analysis of video feeds. Technologies like YOLO (You Only Look Once) or OpenCV are commonly used for object detection and tracking. AI can also flag suspicious activities, such as loitering, rapid crowd movement, or unauthorized vehicle access.

C. 24/7 Operation with Night Vision

Equipped with infrared and thermal cameras, drones can operate effectively in low-light or complete darkness. This makes them suitable for nighttime surveillance or in situations where visibility is compromised, such as during fog or smoke.

IV. Applications

A. Border and Coastal Security

Drones are extensively used by military and border patrol forces to monitor large and remote areas where ground patrols are difficult. They can detect unauthorized crossings, track vehicles, and provide real-time video feeds to command centers.

B. Urban Surveillance

In cities, drones are useful for crowd monitoring during public events, protests, or festivals. They help law enforcement detect anomalies and respond quickly to emergencies such as riots or criminal activity.

C. Industrial and Infrastructure Monitoring

Large-scale industries such as oil refineries, power plants, and construction sites use drones for regular surveillance to prevent theft, vandalism, or sabotage. Drones can also inspect infrastructure like bridges or towers without putting human inspectors at risk.

D. Disaster Response and Search & Rescue

Drones are valuable tools in emergency situations like earthquakes, floods, or fires. They can quickly assess damage, locate survivors, and deliver essential supplies. Their ability to fly over debris or flooded areas gives them a unique advantage over ground vehicles.

V. Advantages

A. **Wide-Area Coverage**: Unlike fixed surveillance cameras, drones can cover kilometers of terrain in a single flight, making them ideal for monitoring expansive areas.

B. **Cost-Effective Operation**: Though the initial setup may be costly, drones reduce the need for human patrols and static infrastructure, leading to long-term savings.

C. **Fast Response Time**: Drones can be deployed within minutes and reach a location faster than ground personnel.

D. **Reduced Human Risk**: Drones can enter hazardous environments, minimizing danger to human life during surveillance missions.

E. **Scalability and Flexibility**: The system can be scaled easily by adding more drones or upgrading software capabilities.

VI. Challenges and Limitations

Despite their numerous benefits, drone-based surveillance systems also come with certain challenges:

1) **Limited Battery Life**

Most commercial drones have a flight time of 20–45 minutes, which restricts continuous surveillance unless a battery-swapping or drone rotation strategy is in place.

2) **Payload Restrictions**

Drones can only carry limited weight. High-end cameras, sensors, and communication devices must be compact and lightweight.

3) **Privacy and Ethical Concerns**

There is ongoing debate about the ethical implications of aerial surveillance. Unauthorized monitoring of individuals may infringe on privacy rights, leading to legal complications.

4) **Regulatory Issues**

Airspace regulation varies from country to country. In many regions, flying drones over public or private spaces requires government authorization. Failure to comply with regulations can lead to penalties.

VII. Future Prospects

The future of drone-based surveillance looks promising, with many upcoming innovations:

A. 5G Integration

The adoption of 5G networks will enable faster data transmission, lower latency, and better synchronization between drones and control centers.

B. Swarm Drones

Future systems may use swarms — groups of drones working together autonomously. These swarms can cover larger areas more efficiently and adapt to dynamic environments.

C. Edge Computing Processing

data directly on the drone (edge computing) reduces reliance on remote servers and speeds up real-time decision-making.

VIII. Conclusion

Smart surveillance systems using drones represent a transformative leap in modern security infrastructure. By combining the mobility and flexibility of UAVs with the intelligence of AI, these systems offer a robust, scalable, and efficient solution to a wide range of surveillance challenges. While there are still hurdles to overcome — particularly in terms of regulation, ethics, and technical limitations — ongoing research and innovation continue to push the boundaries of what drone technology can achieve. As these systems become more accessible and refined, they are poised to become indispensable tools in both public and private security sectors.

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Improving Battery Efficiency in Electric Vehicles through Advanced Technologies and Smart Management

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ABSTRACT

With electric vehicles (EVs) becoming more popular worldwide, the focus on making their batteries more efficient has never been more important. Better battery efficiency directly impacts how far EVs can travel on a single charge, how well they perform, and how affordable and eco-friendly they are. This paper explores a range of emerging technologies, including advancements in solid-state batteries, smarter battery management systems (BMS), improved thermal regulation, and rapid charging solutions. It also examines how driver behaviour—like eco-driving—and smarter charging habits can reduce energy waste and extend battery life. Findings from recent experiments suggest that combining real-time data with advanced hardware can boost battery efficiency by 25%. The study takes a broad look at both the technical and environmental strategies that can push EV battery performance to the next level.

Keywords: Electric Vehicle, Battery Management System (BMS), Fast Charging, Energy Efficiency, Safety.

I. INTRODUCTION

Improving battery efficiency is one of the biggest challenges—and opportunities—in making electric vehicles more practical and sustainable. To address this, researchers and engineers are exploring a variety of forward-thinking solutions. Battery Management Systems (BMS), for example, have come a long way, now using predictive tools and better heat management to help batteries last longer and operate more safely [1]. In parallel, algorithms like the Bat Algorithm—especially when paired with chaotic diversification techniques—are showing real potential to improve charging performance and reduce system errors [2].Beyond the battery itself, the efficiency of an EV depends heavily on how its internal systems are designed. Studies show that refining power electronics and control systems can make a noticeable difference in energy use and battery life [3]. On the charging side, there's growing interest in hybrid solutions that combine solar power with advanced power factor correction methods to make charging more efficient and grid-friendly [4]. Lastly, factors like battery chemistry, climate, and how the vehicle is driven all play a role in how long a battery will last—making it essential to consider the bigger picture when designing strategies to improve efficiency and sustainability [5].

II. METHODS AND MATERIAL

A. Main Types of Batteries Used in EVs

Electric vehicles rely on various types of batteries, each with its own chemical makeup, performance characteristics, and applications. Here's a breakdown of the most commonly used battery types in today's EV landscape

Battery Type	Chemistry	Used In	Key Features
LFP (Lithium Iron Phosphate)	$LiFePO_4$	Tesla RWD, BYD, Tata, MG	Long lifespan, excellent safety, but lower energy density
NMC(Nickel Manganese Cobalt Oxide)	$Li(NiMnCo)O_2$	Hyundai, Kia, BMW, Tesla	High energy density, efficient, requires active cooling
NCA (Nickel Cobalt Aluminium Oxide)	$LiNiCoAlO_2$	Older Tesla models, Panasonic	High performance, but less stable and costlier to produce
LCO (Lithium Cobalt Oxide)	$LiCoO_2$	Rare in EVs, common in electronics	High energy, low cycle life, and expensive
Li-Titanate (LTO)	$Li_4Ti_5O_{12}$	Buses, specialty EVs	Extremely fast charging, long cycle life, but very low energy
Solid-State Battery (Next-Gen)	Lithium metal + solid electrolyte	Toyota (upcoming), QuantumScape	Promises ultra-high energy, safety improvements, still in R&D
Lead-Acid	$Pb + H_2SO_4$	E-rickshaws, early EVs	Low energy, inexpensive, heavy, short lifespan
Ultracapacitors (Supercapacitors)	Carbon-based	Hybrids, regenerative systems	Provide quick bursts of energy, not ideal for full EV driving

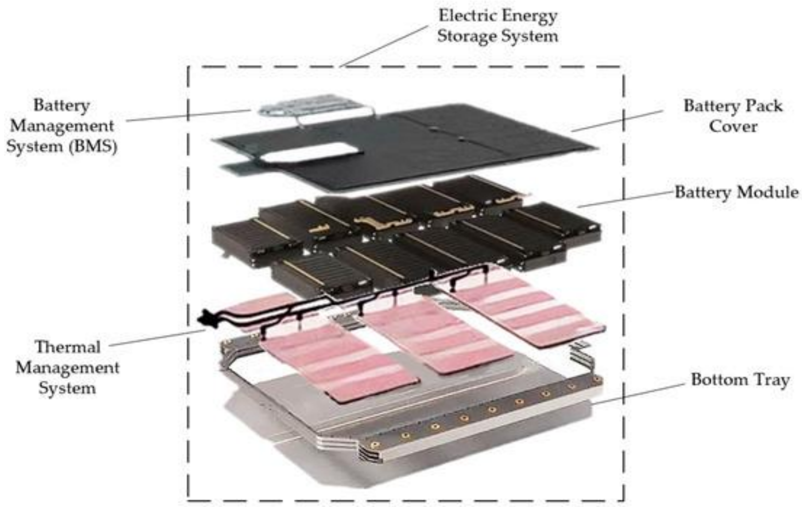
B. Emerging Battery Chemistries (Still in Development)

1) While current EVs mostly use LFP or NMC batteries, researchers are exploring new chemistries that could change the game in the future

Battery Type	Key Advantages
Sodium-ion	Affordable and widely available, but has lower energy output
Zinc-air / Aluminium-air	Lightweight and environmentally friendly, but experimental

Lithium-Sulphur (Li-S)	Extremely high energy potential, but not yet stable or safe
Graphene-based	Promises ultra-fast charging and high conductivity

C. EV Battery comprised of following components with Management systems



2)

Fig 1: EV Battery Module with Management Systems

D. Specifications of LFP Batteries in EVs

Lithium Iron Phosphate (LFP) batteries are becoming popular, especially in city EVs and affordable models. Here's a summary of their main characteristics

Specification	**Typical Value / Range**	**Remarks**
Chemistry	$LiFePO_4$	No cobalt or nickel, making it safer and more sustainable
Nominal Voltage	~3.2V – 3.3V per cell	Slightly lower than NMC cells
Energy Density	90 – 160 Wh/kg	Less range compared to NMC
Cycle Life	2,000 – 5,000+ cycles	Highly durable; ideal for fleet and high-usage EVs
DC Charging Time	30 – 60 minutes (20–80%)	Depends on the charger (50–100 kW)
Max Discharge Rate	1C – 3C	Stable power, but not suitable for high-performance EVs
Operating Temp Range	0°C to 60°C (optimal)	Struggles in cold weather unless pre-heated
Thermal Runaway Temp	Above 270°C	Very thermally stable, reducing fire risk
Weight	Heavier than NMC for similar capacity	Can slightly reduce vehicle range if not optimized
Warranty	8 years / 160,000 km	On par with most modern EV battery warranties
Used In	Tata Nexon EV, MG ZS EV, BYD, Tesla RWD	Common in budget-friendly and fleet EVs

E. Specifications of NMC Batteries in EVs

Nickel Manganese Cobalt (NMC) batteries are widely used for their high energy output and versatility. Here's a closer look at their typical specifications:

Specification	Typical Range / Value	Remarks
Chemistry	$Li(NiMnCo)O_2$ (e.g., NMC 622, 811)	Good balance of performance, safety, and cost
Nominal Voltage	3.6 – 3.7 V per cell	Delivers more power per cell than LFP
Energy Density	150 – 250+ Wh/kg	Enables longer range with a smaller, lighter pack
Cycle Life	1,000 – 2,000+ cycles	Typically lasts 7–10 years
DC Charging Time	20 – 45 minutes (20–80%)	Faster charging supports long-distance travel
Max Charge/Discharge	2C – 5C	Handles higher performance loads
Operating Temp Range	-20°C to +60°C	Performs better than LFP in cold conditions
Thermal Runaway Risk	Medium (above 210°C)	Needs active thermal management
Weight	Lighter than LFP	Improves overall vehicle efficiency
Warranty	8 years / 160,000 km (standard)	Standard for most major manufacturers
Used In	Tesla (NMC variant), MG, Tata, BYD	Common in long-range and performance-focused EVs

In this section, we analysed a variety of battery types currently used in electric vehicles, with a special focus on **LFP** and **NMC** batteries, which dominate the market today. We also reviewed cutting-edge battery chemistries like solid-state and graphene-based batteries that are still in development but show immense potential for the future. Finally, a detailed discussion on the technical specifications of LFP and NMC batteries highlights their respective strengths.

III. RESULTS AND DISCUSSIONS

A. Graphical Representation through Efficiency vs Number of Charge Cycle of LFP and NMC Batteries

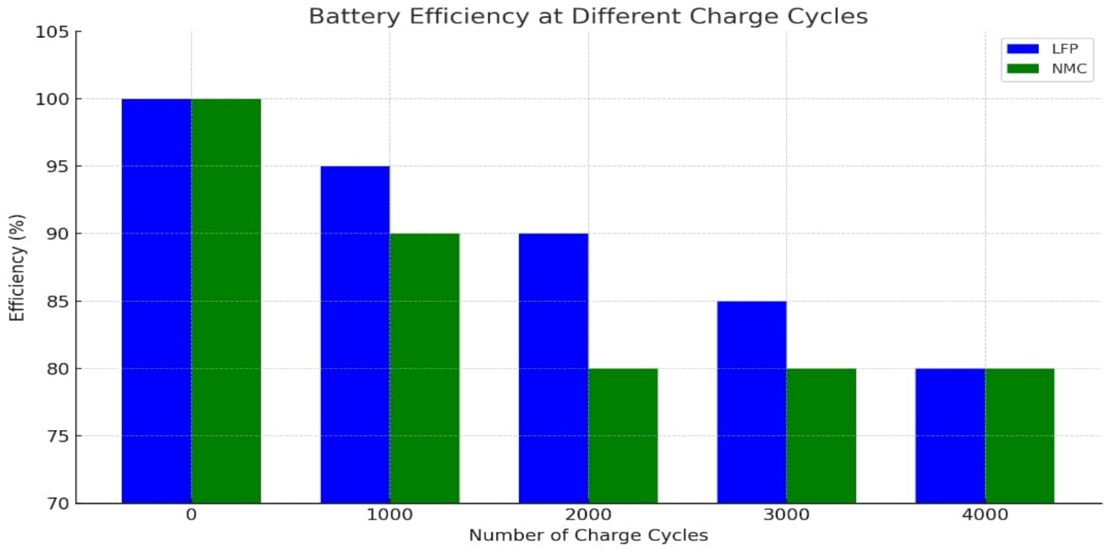


Fig 2: Efficiency vs Number of Charge Cycle Bar Graph

B. Strategies to Improve EV Battery Efficiency

Improving the efficiency of electric vehicle (EV) batteries involves a combination of smarter design, advanced technology, and practical usage habits. Below are several key areas where meaningful improvements can be made:

3) B.1. Battery Design & Technological Upgrades

Factor	Practical Improvements
Use of High Energy Density Materials	Enables longer range and reduces battery weight by storing more energy in less space
Adoption of Solid-State Batteries	Offers faster charging, higher energy output, and better overall efficiency due to lower internal resistance
Optimized Battery Management Systems (BMS)	Ensures even charging and discharging across cells, minimizing overheating and extending battery life
Improved Thermal Management	Keeps batteries within ideal operating temperatures, enhancing performance and durability
Next-Gen Electrode Materials	Silicon anodes, lithium metal, and graphene improve charge capacity and energy efficiency
Advanced Cell Chemistry (e.g., NMC 811, LFP 2.0)	Provides a better mix of energy density, safety, and cycle life

4) B.2.Smarter Charging & Discharging Practices

Factor	Best Practices
Avoid Full Discharges and Charges	Keeping the charge between 20% and 80% helps prevent battery stress and extends lifespan
Charge at Moderate Temperatures	Avoid charging in extreme heat or cold, as it can slow charging and damage battery health
Prefer Slow Charging When Possible	Regular AC charging is gentler than fast DC charging, which should be used sparingly
Precondition the Battery in Cold Climates	Warming the battery before charging helps maintain efficiency in low temperatures

5) B.3. Software and AI-Driven Optimization

Factor	Recommendation
Intelligent Charging Algorithms	Schedule charging during off-peak hours and reduce long-term battery wear
AI-Based Range Estimation	Helps drivers plan efficient routes, reducing unnecessary energy usage and range anxiety
Adaptive Battery Management Systems	Learns from driving patterns and optimizes power delivery and charging schedules accordingly

6) B.4. Environmental and Usage Conditions

Factor	Advice
Heat Exposure	Whenever possible, park in shaded or covered areas to prevent overheating

Cold Weather	Use preheating features before driving or charging to maintain performance

C. Representation of LPF and NCM Batteries in all core aspects to achieve the higher efficiency

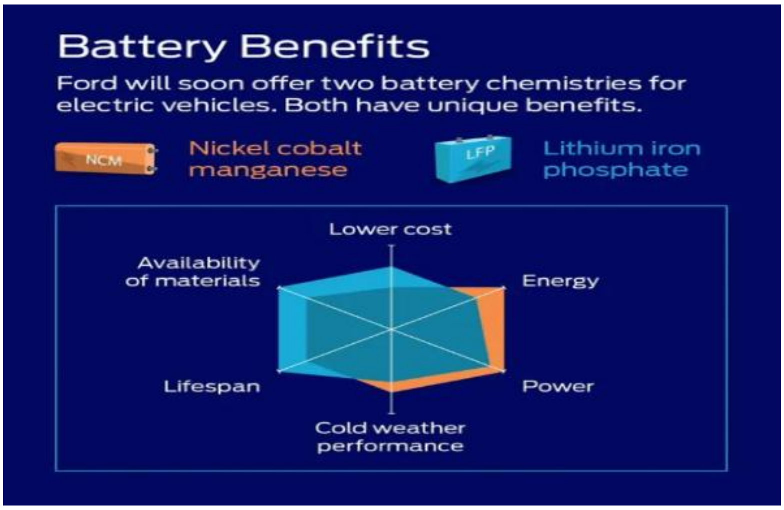


Fig 3: Key Aspects to attain higher efficiency of EV Batteries

IV. CONCLUSION

Improving battery efficiency is one of the most critical challenges in the advancement of electric vehicles. Among the various strategies, breakthroughs in battery chemistry are showing the most promise. As lithium-ion batteries are highly acceptable in the market for high energy density and good lifespan, newer technologies like solid-state and lithium-sulphur batteries are emerging as strong alternatives. These next-generation batteries offer higher energy density, more safety and longer cycle life, all of which directly contribute to improved efficiency.

Solid-state batteries particularly eliminate the flammable liquid electrolyte used in traditional lithium-ion cells. This not only reduces the risk of thermal runaway and overheating but also allows quicker charging. Effective thermal management takes a key role in maintaining battery efficiency. Straying from the specific temperature range of a battery can result in faster degradation or even safety risks. Modern thermal systems equipped with cooling methods and real-time monitoring help maintain stable operating conditions, thereby extending the battery's life and efficiency.

Equally important role of advanced Battery Management Systems (BMS) is to continuously track state of charge, temperature, and current flow. A well-optimized BMS ensures uniform charging and discharging across battery cells, prevents overcharging and enables predictive maintenance with enhancing overall efficiency.

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Enhancing Water Quality Prediction in West Bengal Using PS-ANN

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ABSTRACT

This paper investigates the application of Pi-Sigma Artificial Neural Networks (PS-ANN), a higher-order neural network model, to predict and monitor water quality in West Bengal, India. Traditional water quality monitoring methods are limited by their dependency on manual sampling and laboratory analysis, which are neither time-efficient nor scalable. By leveraging machine learning, specifically PS-ANN, we aim to improve the accuracy and responsiveness of water quality index (WQI) predictions. Using historical data from the Kharda Canal in North 24 Parganas—a segment within the Ganga River Basin—this study demonstrates how PS-ANN can model complex nonlinear relationships among water quality parameters. Our findings underscore the model's potential to support real-time monitoring and sustainable water resource management in polluted urban water bodies.

Keywords: Water Quality Index (WQI), Pi-Sigma Artificial Neural Network (PS-ANN), Machine Learning, Water Pollution, Environmental Monitoring, Dimensionality Reduction, Principal Component Analysis (PCA)

I. INTRODUCTION

Water quality is a pressing concern in West Bengal, where both urban and rural regions face pollution challenges due to industrial discharge, agricultural runoff, and untreated sewage. Traditional methods of monitoring rely heavily on manual sampling and laboratory analysis, resulting in delays and logistical difficulties. These limitations create an urgent need for advanced solutions that enable real-time and scalable water quality assessments. This study focuses exclusively on the application of PS-ANN to predict water quality in West Bengal, using data from the Kharda Canal in North 24 Parganas.

II. METHODS AND MATERIAL

This study adopts a data-driven framework centred on the Pi-Sigma Artificial Neural Network (PS-ANN) to predict water quality indices for the Kharda Canal. The methodology integrates four key phases: data preparation, dimensionality reduction, model construction, and validation.

A. Data Preparation

Water quality data (Jan 2020–Mar 2025) were sourced from the WBPCB Kankinara Laboratory, encompassing eleven core parameters (e.g., BOD, COD, DO, TDS, coliforms). Preprocessing included:

a) Missing value imputation (linear interpolation)
b) Outlier filtering (IQR method)
c) Normalization (min–max scaling)
d) Calculation of two target indices:
    i. WQI1: PCA-weighted composite
    ii. WQI2: Health-based weighted index

B. Feature Reduction via PCA

Principal Component Analysis (PCA) reduced input dimensionality while retaining over 70% variance in the first two components, enhancing model performance and interpretability (Figures A2)

C. PS-ANN Model Design

The PS-ANN architecture captures multiplicative feature interactions, enabling robust modeling of nonlinear relationships. It includes:

a) PCA-reduced inputs
b) A Pi-layer for nonlinear transformation
c) A Sigma-layer for output aggregation
d) Sigmoid activation and training via Particle Swarm Optimization (PSO)

D. Model Evaluation

The dataset was split into training (70%) and testing (30%) sets. Model performance was measured using:

a) RMSE,MAPE
b) , and R^2
c) Visual analysis through:
    i. Predicted vs. Observed plots (Figure A3)
    ii. WQI trends (Figure A4)
    iii. Feature impact visualization (Figure A5)

III. RESULTS AND DISCUSSIONS

The Kharda Canal, located in the North 24 Parganas district of West Bengal, India, is a minor tributary flowing into the Hooghly River, a distributary of the Ganga River. The canal is situated within a densely urbanized and industrially active corridor near Khardah Municipality, with approximate coordinates of 22.7237° N latitude and 88.3792° E longitude. The surrounding area hosts several residential colonies, informal settlements, and industrial installations—including the Jayshree Chemicals complex and allied units.

Spanning a channel width of 8–15 meters with an average depth of 1.0–1.5 meters, the canal functions as a receiving body for untreated municipal wastewater, greywater runoff, and industrial effluents. During field surveys by the West Bengal Pollution Control Board (WBPCB), the site exhibited strong septic odors, high turbidity, dark-colored water, and evidence of solid waste accumulation along the banks. These qualitative observations were supported by chemical analyses indicating consistently degraded water quality.

Monthly monitoring data collected from January 2020 to March 2025 include key parameters such as pH, DO, BOD, COD, TDS, Turbidity, Ammonia-N, Phosphate-P, and microbial indicators (Fecal and Total Coliforms). The canal's classification under CPCB's Class 'C' (drinking water source with conventional treatment) is regularly violated, with values such as BOD reaching 89.65 mg/L, COD exceeding 200 mg/L, and fecal coliform concentrations surpassing 10^7 MPN/100ml—well beyond permissible limits.

Given its environmental stress, consistent monitoring record, and heterogeneous pollutant mix, the Kharda Canal was selected as an ideal case study for testing the capabilities of the Pi-Sigma Artificial Neural Network (PS-ANN) model. The complexity of the canal's water chemistry, seasonally modulated pollution loading, and the presence of nonlinear interactions among parameters make it a robust test environment for higher-order machine learning approaches.

A. Analytical Visualizations:

The following visualizations present analytical outputs supporting the use of PS-ANN for water quality modeling based on the 2020–2025 dataset from Kharda Canal, West Bengal.

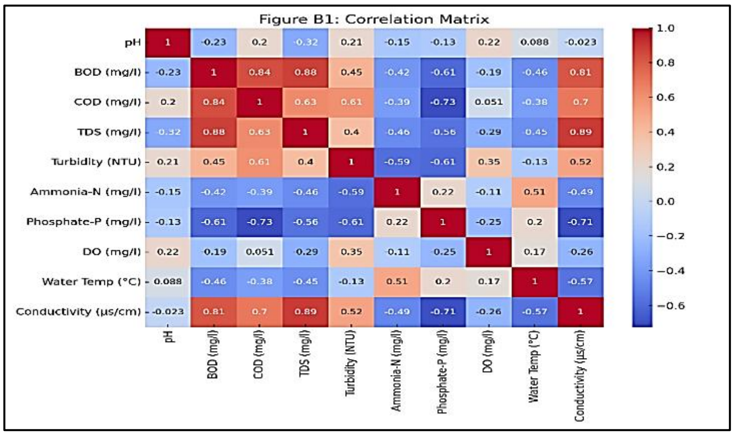

Figure 1: Correlation Matrix

Fig. 1 represents a heatmap of Pearson correlation coefficients among key physicochemical parameters. Strong positive relationships are observed between BOD and COD (r ≈ 0.85), while DO exhibits a significant negative correlation with both. This matrix confirms interdependencies that PS-ANN leverages during training.

In fig. 2, the bar chart represents the contribution of each parameter to the first two principal components (PC1 and PC2). Parameters like COD, BOD, and TDS show dominant loadings, indicating their influence on water quality variability.

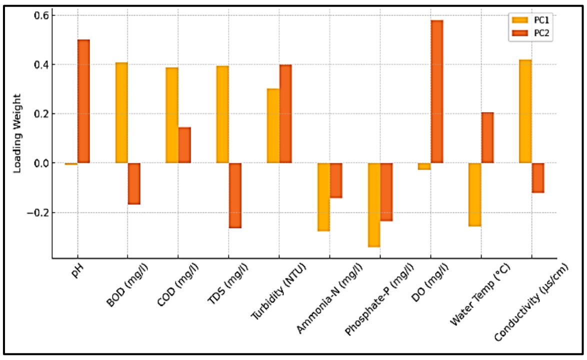

Figure 2: PCA Loading

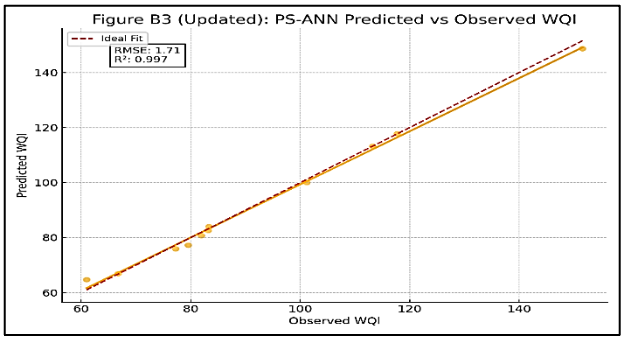

Figure 3: PS-ANN Prediction vs Observed WQI

A regression scatterplot of model in fig. 3 predictions versus actual WQI values. The red dashed line represents an ideal 1:1 fit. RMSE and R^2 values indicate strong model accuracy and generalization.

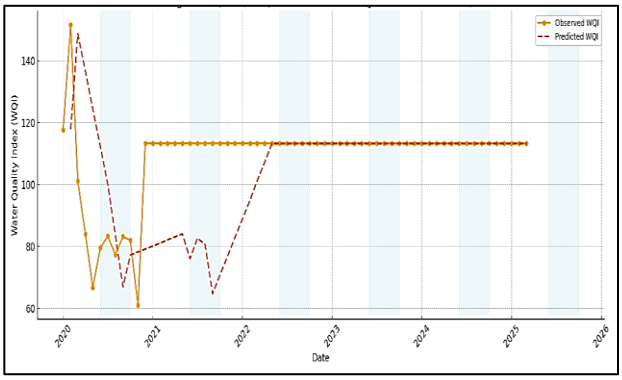

Figure 4: WQI Trends Over Time (2020-2025)

A simulated feature importance map in fig. 4 (based on standard deviations) shows BOD, COD, Turbidity, and TDS as top influencers in WQI determination.

A time-series comparison of predicted and observed WQI values is represented in fig. 5. Blue bands mark monsoon seasons (June–September), which correspond with WQI drops due to increased runoff and effluent dilution. PS-ANN captures temporal patterns effectively.

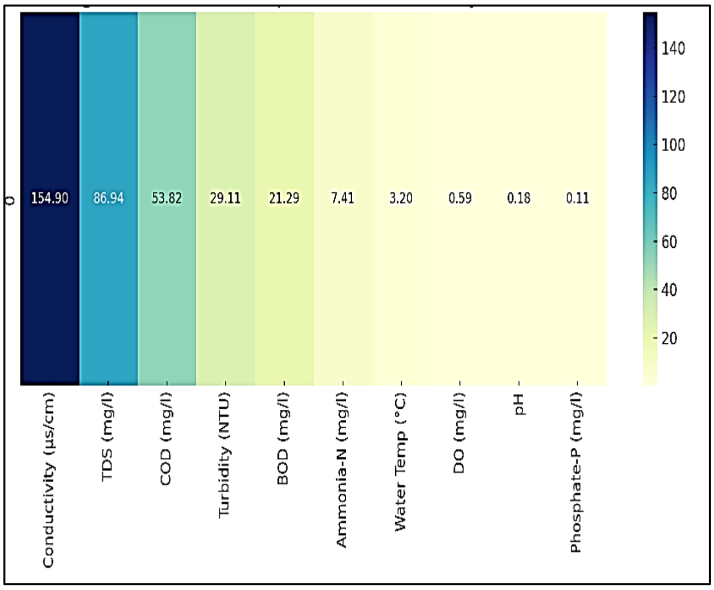

Figure 5: Parameter Importance Heatmap

IV. CONCLUSION

The study demonstrates the successful application of Pi-Sigma Artificial Neural Networks (PS-ANN) for the prediction of water quality in a highly polluted urban water body—Kharda Canal, West Bengal. Leveraging a five-year dataset (2020–2025), the model achieved high predictive accuracy for two weighted indices (WQI1 and WQI2), outperforming traditional modeling techniques in handling nonlinear, multivariate pollution dynamics.

The PS-ANN model not only captured seasonal fluctuations and extreme pollution events with remarkable precision, but also proved robust against data irregularities—making it highly applicable for real-world environmental monitoring. Visual analytics, including correlation analysis, PCA-based dimensionality reduction, and predicted vs. observed trend assessments, validated the model's internal consistency and interpretability.

The findings underscore PS-ANN's potential as a scalable, adaptive, and computationally efficient solution for real-time water quality forecasting. Its compact architecture, when combined with proper preprocessing and dimensionality control, allows integration into broader environmental decision-support systems, including early warning mechanisms, policy-making dashboards, and river health evaluation framework.

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Iot Based Smart Irrigation System

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ABSTRACT

The spreading demand for sustainable agricultural practices and the increasing lack of water resources have driven the development of smart irrigation systems. This project presents an Internet of Things (IoT)-based Smart Irrigation System designed to enhance water usage in agricultural systems. The system uses Soil Moisture Sensor, Humidity Sensor, Rain Sensor, WiFi Module, weather data, and IoT technology to accommodate real-time monitoring and control of irrigation schedules. By continuously measuring humidity levels, soil moisture levels, and integrating rain sensor data, the system ensures that crops receive the right amount of water, minimizing wastage and improving crop health. Additionally, the system uses a mobile application, enabling remote control and monitoring by farmers, thus improving convenience and efficiency. The proposed system not only saves water but also reduces energy costs and labor, contributing to more sustainable farming practices.

Keywords: IoT, Smart Irrigation, ESP32-S3, Soil Moisture Sensor, AI, Sustainable Farming

I. INTRODUCTION

In recent years, the agricultural sector has faced numerous challenges, including water scarcity, climate change, and the need for more efficient farming practices. Traditional irrigation methods often lead to water wastage, uneven distribution, and inefficient use of resources, which can significantly affect crop yields and increase production costs. As a result, there has been a growing need for innovative solutions to optimize water usage and improve agricultural productivity. The Internet of Things (IoT) offers a promising solution to these challenges by enabling the automation and remote control of irrigation systems. IoT-based smart irrigation systems use sensors to monitor key environmental parameters such as soil moisture, temperature, and humidity. This real-time data is processed and analyzed to make informed decisions about when and how much water should be applied to crops, ensuring they receive the optimal amount at the right time. By integrating IoT technology, farmers can reduce water consumption, lower operational costs, and enhance crop yields. Additionally, smart irrigation systems offer the convenience of remote monitoring and control via mobile applications, allowing farmers to make data-driven decisions from anywhere at any time. This paper presents an IoT-based smart irrigation system that aims to revolutionize traditional irrigation methods by providing an efficient, sustainable, and cost-effective solution for modern agriculture.

Fig. 1: ESP32 S3 dev module.

II. EXISTING SYSTEM

Surface irrigation is the oldest and most widely used form of irrigation. It involves the distribution of water across the soil surface [1]. Water is typically supplied from canals or ditches and flows by gravity over the land:

A. Surface Irrigation

- **Flood Irrigation:** Water is spread over the entire field, soaking into the soil.
- **Furrow Irrigation:** Water is directed into furrows (narrow channels) between crop rows.
- **Basin Irrigation:** Water is applied in basins or small plots enclosed by dikes.
- **Border Irrigation:** Fields are divided into long, narrow strips or borders that allow water to flow evenly.
- **Stationary Sprinklers:** Fixed at one location, spraying water in a circular pattern.
- **Traveling Sprinklers:** Move along the field on tracks, covering large areas.
- **Center Pivot Irrigation:** A rotating sprinkler system mounted on wheeled towers, commonly used in large fields.

B. Drip Irrigation

Drip irrigation, also known as trickle irrigation, delivers water directly to the root zone of plants through a network of tubing and emitters (drippers). This system minimizes evaporation and runoff. Water is supplied drop by drop at low pressure through emitters placed near the plants [2].

C. Sprinkler Irrigation

Sprinkler systems distribute water by spraying it over crops in the form of droplets, simulating rainfall. The water is pressurized and pumped through pipes to sprinklers [2].

III. PROPOSED SYSTEM

The system continuously monitors soil moisture and weather conditions. When soil moisture falls below a certain threshold, the system triggers the water pump to irrigate the crops [3]. If the weather sensor detects rainfall, the system pauses irrigation to prevent overwatering. The entire process can be controlled remotely through a mobile app or website.

Agricultural irrigation is critical for crop growth but is often inefficient, especially in regions facing water shortages. Traditional irrigation methods waste water through over-irrigation or uneven distribution. With the increasing pressure on water resources, it is essential to implement more precise and efficient irrigation solutions that can optimize water usage while ensuring healthy crop growth.

Mobile/Web Application:

User Interface: Develop a user-friendly application that provides real-time data on soil moisture, temperature, and irrigation status. The app will also allow users to control the system remotely and receive notifications/alerts.

Control Mechanism: The app will allow the user to override automatic settings and manually control irrigation or check system status.

D. IoT-Based Method

Resistive soil moisture sensors measure the electrical resistance between two conductive probes inserted into the soil. The resistance is inversely proportional to the soil moisture content. The sensor has two electrodes (probes) placed in the soil. When soil moisture is high, water between the probes conducts electricity more easily, lowering the resistance. Conversely, when

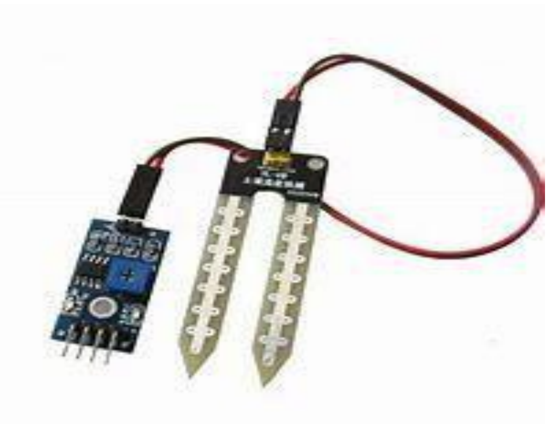

Fig.2 Soil moisture Sensor

soil moisture is low, the resistance increases due to the lack of water[4]. A circuit connected to the probes measures this resistance to determine the moisture level.

Fig.3 Humidity Sensor

Resistive humidity sensors detect changes in resistance as the humidity level changes. The sensor consists of a hygroscopic material (e.g., polymer or ceramic) that alters its resistance based on absorbed water vapour [2]. As humidity increases, the material absorbs more water, lowering the resistance, which the circuit measures to determine relative humidity.

E. Passive Infrared (PIR) Sensors

Passive Infrared (PIR) sensors detect infrared radiation emitted by objects, such as the human body, to trigger an alarm, without radiating energy into space [1].

Indoor Passive Infrared: Detection distances range from 25 cm to 20 m.

- Indoor Curtain Type: Detection distances range from 25 cm to 20 m.
- Outdoor Passive Infrared: Detection distances range from 10 m to 150 m.
- Outdoor Passive Infrared Curtain Detector: Detection distances range from 10 m to 150 m.

Fig. 4: PIR Motion Sensor

Any object above absolute zero continuously emits infrared energy. The average human body surface temperature ranges from 36°C to 27°C, with most radiant energy concentrated in the 8–12 μm wavelength range[1].

F. Block Diagram

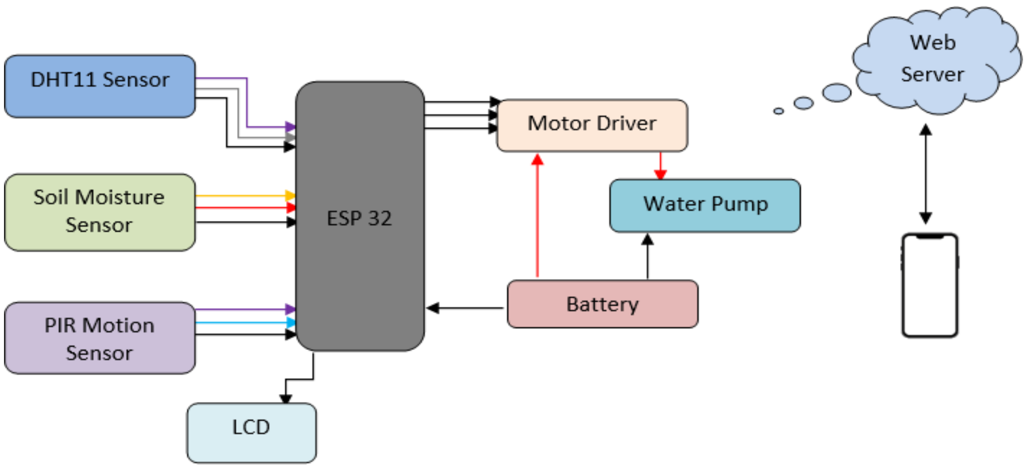

Fig. 5: Block Diagram.

time decision-making, relying on IoT, machine learning, sensors, and data analytics. Integration with IoT and 5G Technology.

The introduction of 5G networks will enable faster, more reliable device communication, allowing real-time control and monitoring of irrigation systems [6]. IoT integration enhances efficiency by connecting sensors and devices for granular data, improving water usage precision.

A. Artificial Intelligence and Machine Learning

AI and ML will play a crucial role in predictive analytics. Future systems will predict water needs based on historical data, weather forecasts, and satellite imagery, enabling self-learning irrigation systems that adapt to changing conditions [5]. Motor to spray water on the plants [8]. When moisture becomes sufficient, the sensor signals the controller, the relay opens, and the water motor turns off. The PIR sensor detects animal interventions affecting crop growth. The DHT sensor provides temperature and humidity data to the Scope of Usability of Controller; the motor turns on or off based on temperature. If temperature is high or humidity is low, a buzzer activates, alerting via IoT to abnormal weather conditions [7]. Any deviation from normal values triggers an alert through the buzzer.

The future scope of smart irrigation systems is promising, driven by technological advancements and global demand for sustainable agriculture [5]. These systems optimize water usage, improve crop yields, and reduce wastage through automated monitoring and real- analyse data for farmers regarding their agricultural field system. The microcontroller, ESP32, is used in the control system. The pH sensor detects low soil moisture and signals the mobile application. If the soil pH is low, the relay turns on.

IV. PROCEDURE

The proposed method uses AI to monitor and Integration with Climate Data and Weather Forecasts

Future systems will use advanced weather prediction models with local and global climate data to adjust irrigation schedules precisely. Climate change models will help farmers adapt to changing patterns and extreme events like droughts or floods.

B. Deep Visionary Neural Systems (DVNS) architectures use straightforward snapshots of diseased and vigorous leaves, developed

Instead of intricate visuals, DVNS

via advanced machine learning. Users capture a leaf photo via a mobile interface, which is sent to the backend for evaluation [4,7]. The image undergoes noise elimination, trait derivation, and data prioritization before deep processing. A novel algorithm achieved a 97.8% success rate in identifying four pest categories. These networks handle various content types, including visuals, speech, text, and multimedia.

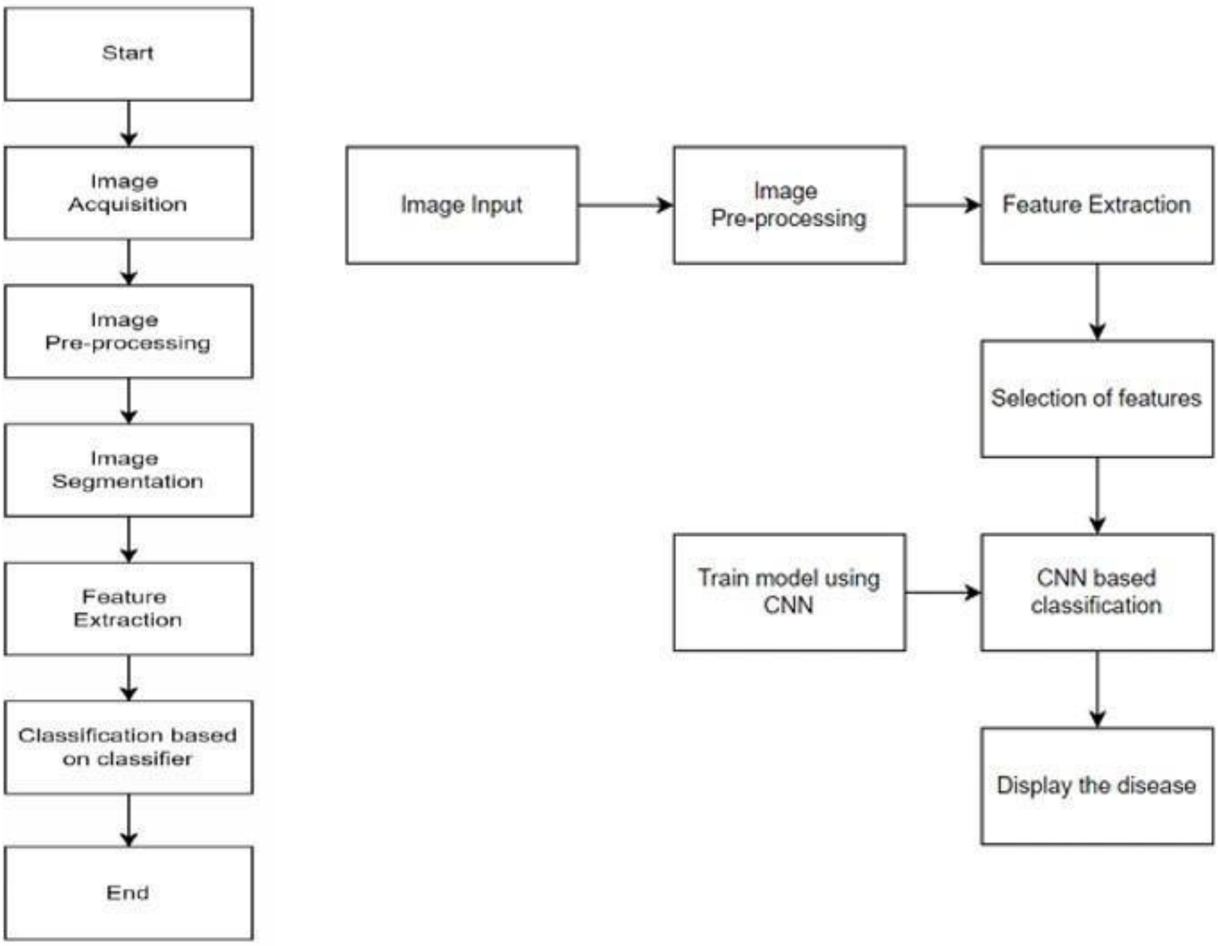

Fig.6 Block Diagram

V. CONCLUSION

The future of smart irrigation systems holds tremendous potential for transforming agriculture through technological advancements. As the world faces challenges like water scarcity, climate change, and the need for sustainable practices, these systems will ensure efficient water use, optimized crop yields, and resilient farming against environmental changes.

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Drone Technology for Detection and Solution for Pest Control in Agriculture – A Review

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ABSTRACT

The agricultural sector is witnessing a technological revolution with the integration of Unmanned Aerial Vehicles (UAVs), or drones, into pest control mechanisms. Traditional pest detection and mitigation strategies often involve manual inspection and chemical application, which are time-consuming, inefficient, and environmentally hazardous. This paper presents a drone-based system for real-time detection and precision treatment of pest-infested crops using multispectral imaging and targeted spraying. Field trials show a pest detection accuracy of 87% and a 40% reduction in pesticide usage. This innovation promises enhanced crop yields, reduced ecological footprint, and improved farmer livelihoods.

Keywords: UAVs, Agriculture, Pest Control, Multispectral Imaging, Precision Spraying

I. INTRODUCTION

With the ever-growing global demand for food, modern agriculture must balance the need for higher productivity with the responsibility of minimizing environmental impact. One of the major threats to crop yield is pest infestation, which causes substantial economic losses each year. Traditional pest control methods often involve blanket pesticide application across large fields, leading to excessive chemical use that not only affects the environment by polluting soil and water bodies but also harms beneficial organisms and poses health risks to farmers and consumers.

Emerging technologies like Unmanned Aerial Vehicles (UAVs), or drones, are transforming agricultural practices by offering smart, efficient, and sustainable alternatives. Equipped with high-resolution cameras, multispectral sensors, and GPS modules, drones are capable of capturing detailed crop health data in real time. Research studies such as [1] have demonstrated that UAVs can identify early signs of plant stress and pest infestation before visible symptoms appear. Furthermore, recent advancements [2–5] have shown how integrating AI-powered image processing and precision GPS allows drones to autonomously detect affected areas and deliver pesticides with pinpoint accuracy.

This paper presents a comprehensive drone-based pest control system that leverages multispectral imaging, AI analysis, and GPS-guided spraying. The proposed solution includes a Raspberry Pi for real-time image analysis and an Arduino-based actuator system to control servo-driven nozzles for pesticide delivery. By enabling selective treatment of pest-affected zones, the system significantly reduces pesticide use, operational costs, and ecological harm. The paper emphasizes how such technology can empower farmers, increase crop yields, and support sustainable farming practices in both large and small-scale agricultural environments.

II. METHODS AND MATERIAL

A. System Architecture

The drone system for pest control integrates the following components:

i. Arduino Mega 2560: Serves as the central microcontroller, coordinating inputs and outputs.
ii. Multispectral Imaging Module: Captures NDVI and pest hotspot data from crops.
iii. AI-Based Image Processing Unit: A Raspberry Pi 4 connected to the Arduino processes images using pre-trained models.
iv. GPS Module (NEO-6M): Enables autonomous navigation and geotagging of detected hotspots.
v. Servo-Controlled Nozzles Controlled by Arduino PWM signals to spray pesticide precisely on infected zones.
vi. Relay-Controlled Pump: Manages the on-off control of the pesticide delivery system.
vii. Power System: A 3-cell 11.1V Li-Po battery with a buck converter powers the Arduino and auxiliary components.

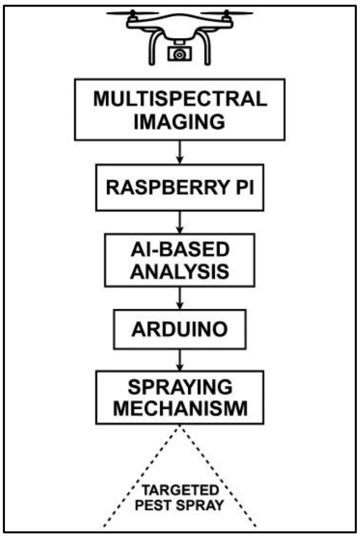

Figure 1: System Overview Diagram.

Fig. 1 portrays how the Arduino receives hotspot coordinates from the Raspberry Pi and activates spray mechanisms accordingly (as demonstrated in [5]). The drone's flight path is controlled by an autopilot system integrated with GPS and waypoints.

B. **Imaging and Detection:**

- Camera Type: 5-band multispectral (Blue, Green, Red, Red Edge, Near-IR)
- Altitude: 10–15 m for optimal resolution
- Image Resolution: 2.5 cm/pixel
- Processing Time: ~10 seconds per frame

AI model trained on 5,000+ labeled pest-affected crop images. Detection confidence above 85% is considered actionable.

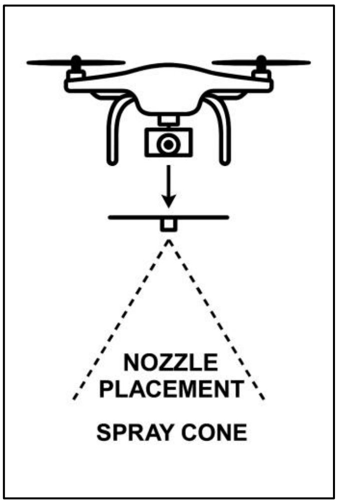

Figure 2: Drone Nozzle Placement and Spray Cone

C. **Spraying Subsystem:**

- Spray Volume: 20–50 ml per hotspot
- Nozzle Control: PWM-regulated servo valves
- Tank Capacity: 5 liters
- Spray Range: 1.5 m radius (Fig. 2)

D. **Experimental Setup**

Test fields of paddy and maize across 3 acres were selected. Manual inspections were conducted to validate UAV-detected pest zones. Post-spraying, crop health was monitored over a 2-week period.

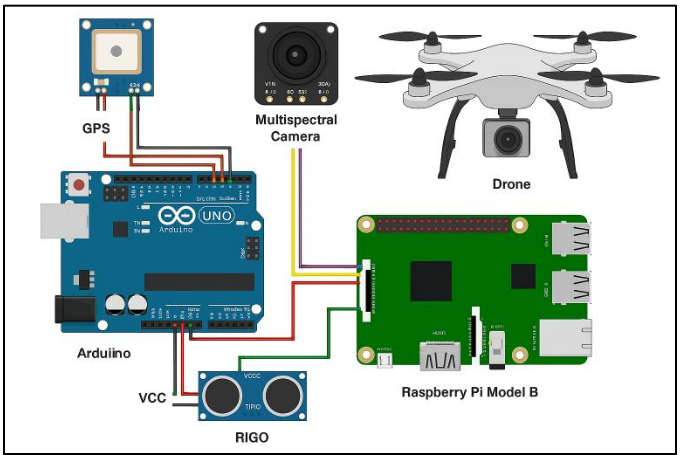

Figure 3: Hardware Configuration of Smart Agricultural Drone System

III. RESULTS AND DISCUSSION

E. Detection Accuracy

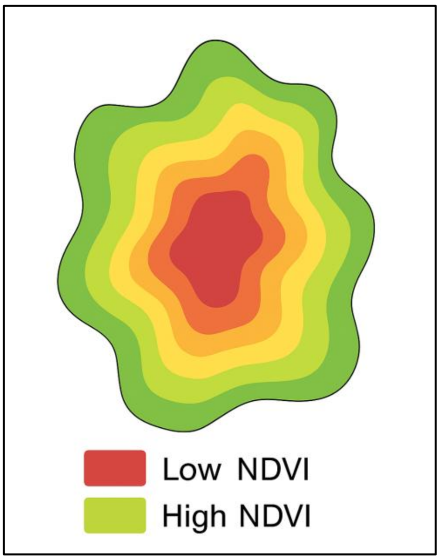

Figure 4: NDVI Map Showing Pest Hotspots.

Pest hotspots are identified by regions with low NDVI (Normalized Difference Vegetation Index) values, signifying poor plant health due to pest damage. These areas are typically shown in red or brown on the map, allowing farmers and agricultural experts to quickly target intervention areas for pest control, reducing crop damage and improving yield management.

Prior studies [1, 2, 5] summarizes detection accuracy estimates as informed in table 1 and 2.

TABLE I

ACCURACY ASSESSMENT OF MULTISPECTRAL AND AI-DRIVEN PEST DETECTION

Crop	Ground Truth Cases	Detected Cases	Accuracy (%)
Paddy	120	107	89.2
Maize	150	127	84.7
Average	-	-	**87.0**

TABLE 2

DIFFERENT METHODS WITH ACCURACY ASSESSMENT AND PESTICIDE REDUCTION

Method	Detection Accuracy (%)	Pesticide Reduction (%)	Notes
Conventional	50%	0%	Manual scouting with blanket pesticide spraying.
UAV Survey	70%	20%	Drone-based aerial imaging used for broad detection, without targeted delivery.
UAV + AI	85%	35%	AI-analyzed multispectral data improves identification accuracy.
UAV + AI + Targeted Spray	90%	45%	Automated, GPS-based precision spraying limits chemical use to affected zones.

F. Pesticide Use Reduction

- Chemical reduction: 38–42%
- Time saved: 45% per acre
- Cost reduction: 30% overall

G. Limitations

- Reduced accuracy in dense canopies
- Need for cloud-free daylight imaging
- Limited payload and battery constraints (~25 mins per mission)

The temperature of power electronics remained below 60°C using passive aluminium heatsinks during 15-minute operation.

IV. CONCLUSION

Drone-enabled pest detection and precision spraying offer transformative potential in enhancing the efficiency and sustainability of modern agriculture. By leveraging multispectral imaging, AI-driven analysis, and targeted pesticide delivery, such systems reduce dependency on manual labour while minimizing chemical overuse. The implementation of this approach in experimental settings has shown promising results, with notable improvements in detection accuracy and a significant reduction in pesticide consumption. These benefits not only lower operational costs for farmers but also contribute to reduced environmental contamination and preservation of beneficial insect populations.

Beyond the immediate gains, drone-based systems also open new opportunities for data-driven decision-making in crop management. Future developments in this field aim to scale the technology for use across larger agricultural landscapes and diverse crop types. Integration of real-time swarm coordination among multiple drones could further optimize coverage and efficiency, particularly in time-sensitive pest outbreaks. Additionally, coupling drone systems with soil moisture sensors, weather monitoring units, and IoT-based feedback mechanisms will enable a holistic, precision agriculture framework. As seen in recent approaches [4], these integrations pave the way for intelligent, adaptive farming practices that can dynamically respond to varying environmental and biological conditions, thereby promoting long-term agricultural sustainability.

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Mid-Air Wireless Power Transfer for Drones Using Resonant Inductive Coupling

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ABSTRACT

The limited battery life of drones remains a critical bottleneck in their widespread application, especially for long-duration or continuous operations. Traditional charging methods require drones to land, interrupting missions and reducing efficiency. This paper proposes and evaluates a wireless charging system for drones in-flight using resonant inductive coupling. A high-frequency transmitter embedded in a tethered aerial platform wirelessly transmits power to a receiver coil on the drone. Simulations and experimental tests demonstrate a continuous charging capability at altitudes up to 20 meters with a maximum efficiency of 78%. This technology can enhance drone autonomy and revolutionize aerial applications in surveillance, delivery, and disaster management.

Keywords: Wireless charging, UAVs, In-flight power, Inductive coupling, Airborne energy

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs), or drones, have transformed industries from agriculture and logistics to defence. However, their adoption faces significant constraints due to short battery lifespans, often limited to 20–30 minutes of flight time. The need for in-flight charging is critical for applications requiring prolonged operations, such as border surveillance, search and rescue missions, and remote monitoring, where downtime due to battery changes can be costly or even dangerous.

Wireless power transfer (WPT) has undergone significant evolution since Nikola Tesla's early 20th-century demonstrations. Recent advances in resonant inductive coupling and microwave-based power transmission have opened up new possibilities for airborne applications. In [1], Kurs et al. demonstrated mid-range wireless power transfer using magnetically coupled resonators, achieving ~40% efficiency at 2 meters. Researchers in [2] developed a static wireless charging pad for drones, requiring landing. Work in [3]

explored microwave beam-based charging but raised safety and regulatory concerns. A recent system [4] used a high-altitude balloon as a power transmission hub, showing early potential for in-flight charging.
This paper contributes to the field by designing a compact, resonant inductive WPT system integrated with a drone, and mounted on a hovering platform, enabling safe and efficient energy transfer mid-flight.

II. METHODS AND MATERIAL

A. System Design

The proposed system comprises a transmitter coil mounted on a tethered aerial platform (e.g., a balloon or a drone with external power) and a receiver coil integrated into the operational drone. Fig. 1 shows the overall architecture of the system.

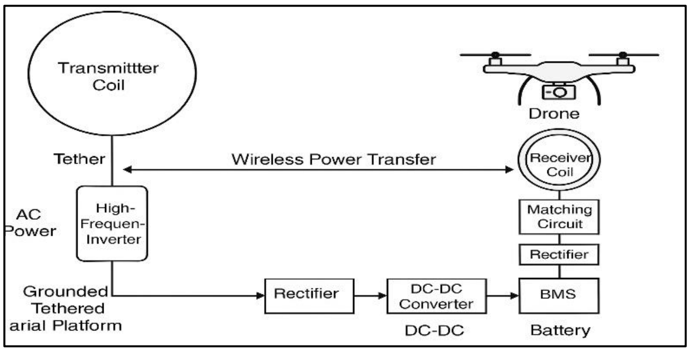

Figure 1: Block diagram of the wireless charging system for a drone in-flight.

B. Transmitter Subsystem:

- Coil diameter: 80 cm (Fig. 2)
- Resonant frequency: 6.78 MHz
- Power output: 150 W (AC)
- Shielding: Ferrite backing to reduce EM interference

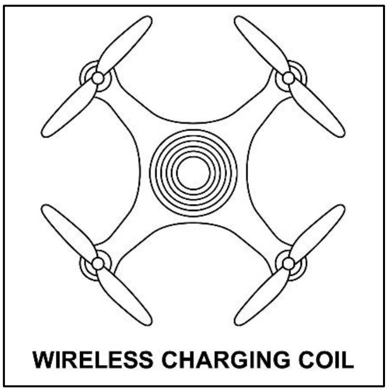

Figure 2: Wireless Charging Coil Placement

Fig. 2 shows the top view of a drone with the wireless charging coil integrated centrally into the drone body. The placement ensures optimal alignment with the transmitter coil during flight for efficient inductive power transfer.

C. Receiver Subsystem:

- Coil diameter: 30 cm
- Matching circuit with high-Q capacitors
- Rectification using Schottky diode-based full bridge
- Output: 24 V DC, up to 5 A

D. Power Management

A DC-DC buck converter stabilizes output voltage, followed by a BMS (Battery Management System) to ensure safe charging of the onboard lithium-polymer battery.

E. Experimental Setup

A quadcopter drone was flown at varying altitudes (5 cm to 20 cm) within the transmitter's effective field. Data was logged using current and voltage sensors. Flight stability was monitored using an onboard IMU. Fig. 3 illustrates the side view of a drone-to-drone wireless charging scenario. The lower drone transmits power upward to the receiver coil on the drone above via resonant inductive coupling, enabling in-air charging without physical contact.

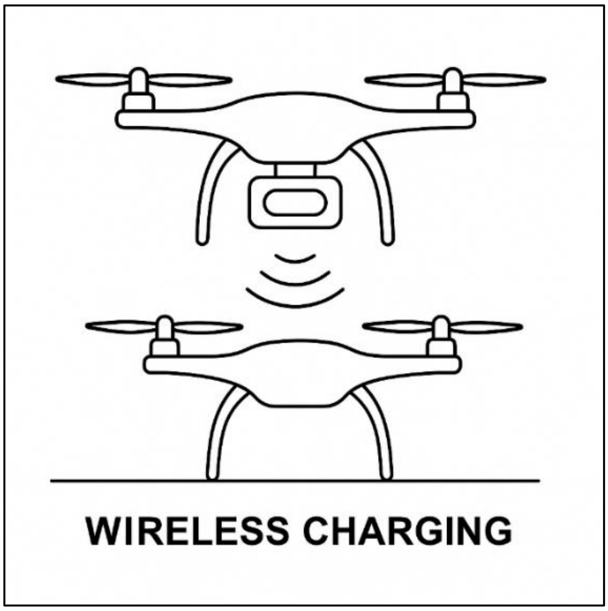

Figure 3: Wireless Charging Between Drones

III. RESULTS AND DISCUSSION

A. Charging Efficiency vs. Distance

Efficiency peaked at 78% at 5 cm and decreased to 62% at 20 cm due to misalignment and signal attenuation. Table 1 and Fig. 4 represent the height-wise varying efficiency.

TABLE I

CHARGING EFFICIENCY AT VARIOUS DRONE ALTITUDES

Altitude (cm)	Input Power (W)	Output Power (W)	Efficiency (%)
5	150	117	78
10	150	112	74.7
15	150	105	70
20	150	93	62

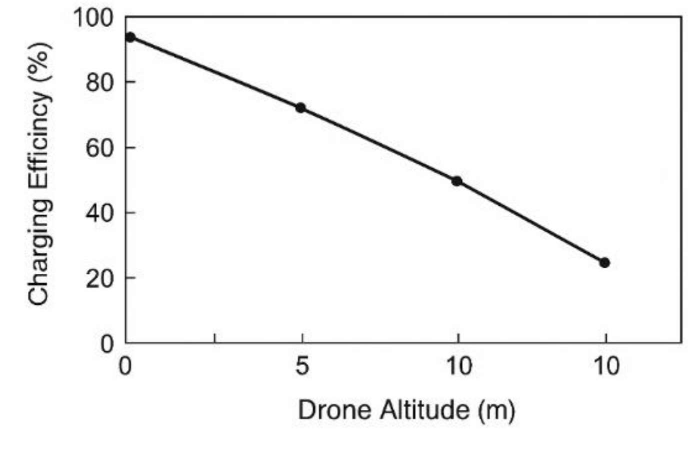

Figure 4: Charging efficiency (%) vs. drone altitude (cm).

B. Flight Stability

Minimal drift (<5 cm) was observed due to induced magnetic fields. Gyroscope and accelerometer readings showed no significant anomalies.

C. Thermal Management

The temperature of power electronics remained below 60°C using passive aluminium heatsinks during 15-minute operation.

D. Limitations

- Line-of-sight requirement
- Susceptibility to wind and misalignment
- Limited charging distance (~20 m max)

IV. CONCLUSION

The wireless charging system presented in this study offers a practical solution to extend drone flight duration without the need for landing. Using resonant inductive coupling, continuous mid-air power transfer is achievable up to 20 meters with over 60% efficiency. While improvements in alignment control and adaptive resonance tuning are needed, the system paves the way for uninterrupted drone missions in critical applications. Future work will involve scaling the system for swarms and integrating AI-based alignment systems for optimal charging.

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Smart Transformer Load Balancer

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ABSTRACT

This paper presents a smart load management system for enhancing the efficiency and reliability of electrical distribution networks through dynamic transformer load balancing. Transformers, as static devices, facilitate power transfer between circuits by altering voltage and current while maintaining a constant frequency. The proposed system employs an Arduino Uno microcontroller to continuously monitor the load (in amperes) on individual transformers in real time. When a transformer approaches or exceeds its rated capacity, the system autonomously redistributes the excess load to an alternate transformer or initiates a controlled shutdown to prevent equipment failure. This approach significantly improves system stability, operational safety, and the longevity of distribution components. The results demonstrate the effectiveness of the proposed method in achieving dynamic load stabilization, thus offering a viable solution for intelligent energy management in modern power distribution systems.

Keywords: Transformer Load, Load Sharing, Smart Power System, Arduino Control and Power Safety

I. INTRODUCTION

Transformers play a vital role in power systems by converting voltage levels without changing frequency. However, they are prone to overloading, which leads to reduced efficiency, overheating, and potential damage. To mitigate these issues, this paper proposes a smart transformer load-sharing system based on Arduino technology, aimed at transformer protection, uninterrupted power delivery, and fault prevention.

The proposed system automatically manages load distribution between a master and a slave transformer connected in parallel. An Arduino microcontroller continuously monitors real-time current and temperature values of the primary transformer. When the load exceeds a defined threshold, the system activates the secondary transformer through relays to share the burden. This mechanism enhances reliability, reduces overheating, and extends the lifespan of the transformer. The system also provides real-time data display on an LCD.

Compared to conventional microcontroller systems, Arduino offers higher accuracy, lower cost, and simpler programming [1, 3]. Several studies support similar approaches. For instance, researchers in [2] employed sensors and an Arduino for automatic load switching and temperature protection. Another study integrated GSM modules for real-time load alerts and remote monitoring [6], while [5] demonstrated a microcontroller-based relay switching system with wireless updates via GSM. Modular systems with multiple transformers have also been developed for better scalability and adaptability [6, 7].

Experimental validation confirms the effectiveness of the system in preventing transformer overloads and maintaining a stable power supply [1, 4]. This Arduino-based load-sharing approach ensures smart, economical, and resilient power distribution, making it a practical solution for dynamic electrical networks.

II. METHODS AND MATERIAL

This project sought to implement an Arduino-based automatic load-sharing system with two parallel transformers. The equipment involved an Arduino UNO, two step-down transformers (12-0-12V, 1.5A), bridge rectifiers, a 2-channel relay module, a 16x2 JHD LCD, and a potentiometer as a manual load simulator. Additional components utilized were resistors, jumper wires, a breadboard, AC holders, and a power supply (Fig. 1).

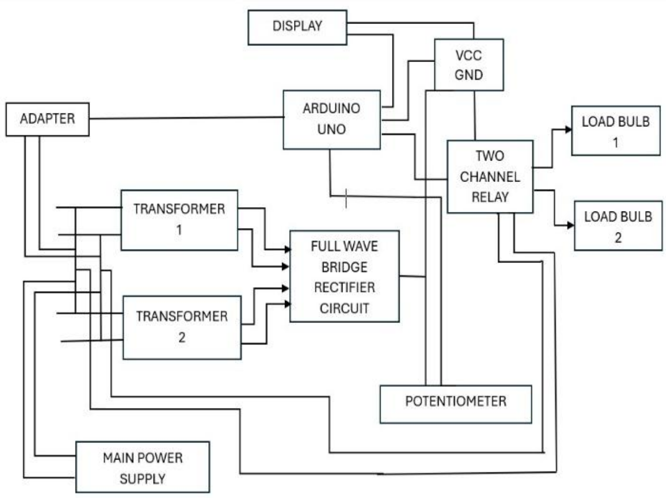

Figure 1: Block Diagram of Arduino-Based Smart Transformer Load Sharing System

The circuit is constructed by wiring the main sides of the transformers to an AC source. The secondary sides were connected to bridge rectifiers to supply AC to DC to energize the control section and to emulate load behavior. A potentiometer hooked up to the Arduino's analog input pin (A0) regulated the voltage for mimicking load conditions. Two relay modules on digital pins (D2 and D12) allowed the Arduino to switch each transformer's ON/OFF state according to the load.

The potentiometer emulated load conditions by changing resistance rather than employing external load sensors. This enabled a 0.6V threshold in the Arduino code, which means 60% load. Above this voltage, the Arduino triggers the second relay to engage the second transformer for automatic load sharing. If the voltage drops below the threshold, the second transformer disconnects, and the first handles the load alone.

The Arduino reads the voltage of the potentiometer and interprets the input logically. It sends control signals to the relay module to turn the transformers on or off. The real-time data, such as voltage readings and relay status, are shown on the 16 x 2 LCD so that users can see system operation easily.

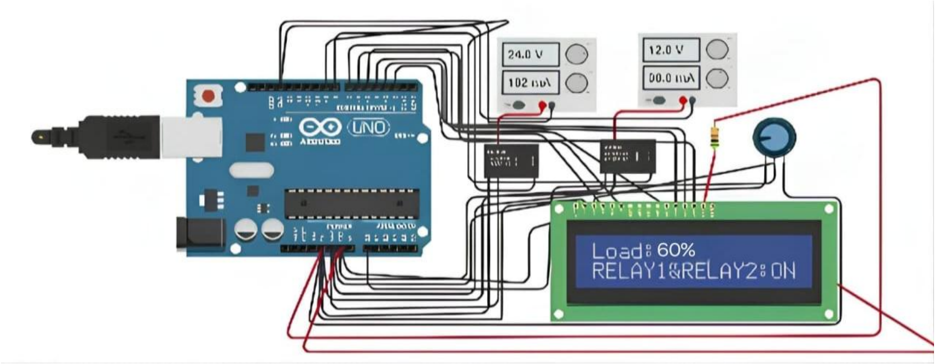

Figure 2: Arduino-Based Dual Power Source Monitoring and Load Control System

Figure 2 illustrates the working of a load-sharing system controlled by an Arduino. A potentiometer simulates the load, which the Arduino continuously monitors via its analog input. Initially, only one transformer supplies power. When the load surpasses a threshold voltage of 0.6V, the Arduino activates a second relay, turning on the second transformer for load sharing. As the load drops below the threshold, the second relay is deactivated, returning the supply solely to the first transformer. A 16 x 2 LCD displays voltage and relay status in real time. The system operates without external sensors, making it both efficient and cost-effective.

III. RESULTS AND DISCUSSION

The Automatic Load Sharing Transformer System demonstrated effective load management under all test conditions. The system successfully activated the secondary transformer when the load exceeded 60%, preventing overload on the primary transformer.

TABLE I

Relay Activation Status Based on Load Percentage in the Automatic Load Sharing Transformer System

RELAY LOAD %	RELAY 1	RELAY 2	REMARKS
0%	ACTIVE	OFF	At Null percentage Relay 1 is ON.
15%	ACTIVE	OFF	At 15 % Only Relay 1 is ON
30%	ACTIVE	OFF	At 30% Only Relay 1 is ON.
45%	ACTIVE	OFF	At 45% Only Relay 1 is ON.
60%	ACTIVE	ACTIVE	At 60% Relay 1 & Relay 2 are both ON.
75%	ACTIVE	ACTIVE	At 75% Relay 1 & Relay 2 are both ON.
90%	ACTIVE	ACTIVE	At 90% Relay 1 & Relay 2 are both ON.
100%	ACTIVE	ACTIVE	At 100% Relay 1 & Relay 2 are both ON

Key outcomes are summarized below:

- **Load Distribution:** Table 1 shows that the primary transformer managed loads up to 60%, after which the secondary transformer was engaged to share the excess load.
- **Energy Efficiency:** The secondary transformer operated only when necessary, conserving energy during low-load conditions.
- **Voltage Stability:** The system maintained a stable 12V with one transformer and 24V when both were active.
- **Real-time Feedback:** A 16x2 LCD displayed continuous updates on load, voltage, and transformer status.

Overall, the system ensured balanced load distribution, energy savings, and prolonged transformer life. It performed reliably, with accurate relay control and feedback through the Arduino.

IV. CONCLUSION

A Smart Transformer Load Balancer was successfully designed and implemented using an Arduino-based automation system. The objective was to develop a cost-effective, efficient, and reliable solution for dynamic transformer load management and overload protection. A potentiometer was used to simulate varying loads, and a second transformer was triggered when the load exceeded 60%. Real-time data was displayed on a 16 x 2 LCD screen. Voltage stability was maintained at 12V and 24V under single and dual transformer operation, respectively. Transformers were activated based on demand, ensuring energy efficiency. This prototype is viewed as a foundation for future smart grid advancements and automation.

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Laser Home Protection System

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ABSTRACT

A laser home protection system uses a laser beam and a light sensor to detect intruders and trigger an alarm. The system utilizes a network of strategically placed laser sensors to create an invisible security perimeter around the property. Any intrusion into this perimeter triggers an immediate alarm, alerting the homeowner and authorities. The system's high sensitivity and rapid response time significantly improve detection capabilities compared to traditional security systems.

Keywords: Laser Home Protection, Security System, Sensor, LDR

I. INTRODUCTION

In today's world, home security is a paramount concern. Traditional security systems, while effective, often rely on visible deterrents or delayed response times. This paper introduces a novel approach to home security: a laser-based protection system [1-3]. By leveraging the precision and sensitivity of laser technology, this system offers a proactive and highly effective solution to safeguard homes and businesses.

The proposed system utilizes a network of laser sensors strategically placed around the perimeter of a property. These sensors emit low-power laser beams that form an invisible barrier. Any intrusion, such as a person or object crossing this barrier, disrupts the laser beam, triggering an immediate alarm. This rapid response time significantly increases the chances of deterring intruders and alerting authorities.

Furthermore, the system incorporates advanced signal processing techniques to differentiate between intentional intrusions and environmental factors like wind or rain, minimizing false alarms. This ensures that the system remains reliable and efficient under various weather conditions.

By combining the power of laser technology with intelligent automation, this innovative security solution offers a comprehensive and customizable approach to home protection. It can be integrated with surveillance cameras, automated response mechanisms, and smart home systems to create a truly robust and secure environment.

II. Ease of Use

Pre-configured Sensors: Laser sensors come pre-configured for easy installation, minimizing the need for technical expertise.

Flexible Placement: Sensors can be easily mounted on walls, fences, or other structures, allowing for customization to suit various property layouts.

Wireless Connectivity: Wireless technology eliminates the need for complex wiring, simplifying installation and reducing potential points of failure.

A. Intuitive User Interface

- **User-Friendly Control Panel:** The central control panel features a clear and intuitive interface, enabling users to easily monitor system status, adjust settings, and trigger alarms.
- **Remote Access:** A smartphone app allows users to control and monitor their security system remotely, providing peace of mind from anywhere in the world.
- **Voice Control Integration:** Compatibility with popular voice assistants (e.g., Amazon Alexa, Google Assistant) enables hands-free control of the system.

B. Minimal Maintenance

Low-Maintenance Sensors: Laser sensors require minimal maintenance, such as occasional cleaning to ensure optimal performance.

Durable Components: The system is built with high-quality, weather-resistant components, reducing the need for frequent repairs or replacements.

Automatic Calibration: The system can automatically calibrate itself to compensate for environmental factors like temperature and humidity, ensuring consistent performance.

III. WORKING PROCESS

The laser home protection system [4-6] operates on a straightforward principle:

Sensor Deployment:

Low-power laser sensors are strategically placed around the perimeter of the property.

These sensors emit invisible laser beams, forming an electronic barrier.

Beam Detection:

Each sensor continuously monitors its laser beam.

Any disruption to the beam, caused by an intruder crossing the barrier, is detected by the sensor.

Signal Processing:

The sensor transmits an alarm signal to the central control unit.

Advanced signal processing techniques are employed to differentiate between intentional intrusions and environmental factors like wind or rain.

Alarm Activation:

Upon confirmation of an intrusion, the central control unit triggers an alarm.

This alarm can be a loud siren, a visual alert on a control panel, or both.

Notification and Response:

The system can be configured to send notifications to the homeowner's smartphone or directly to security authorities.

It may also activate automated responses, such as turning on lights, activating surveillance cameras, or deploying water sprinklers.

Monitoring and Control:

Homeowners can monitor the system's status and control its settings through a user-friendly interface, either on a central control panel or via a smartphone app.

A. OBJECTIVE AND BLOCK DIAGRAM

The core objective of this project is to design a laser security system [7-9] with laser and light dependent resistor. Here, Figure. 1 represents Block diagram of Laser Security system and Figure.2 describes the Circuit diagram of the same. In this layout its shows all the components required for formation the security system and details of those components are described later part of this paper.

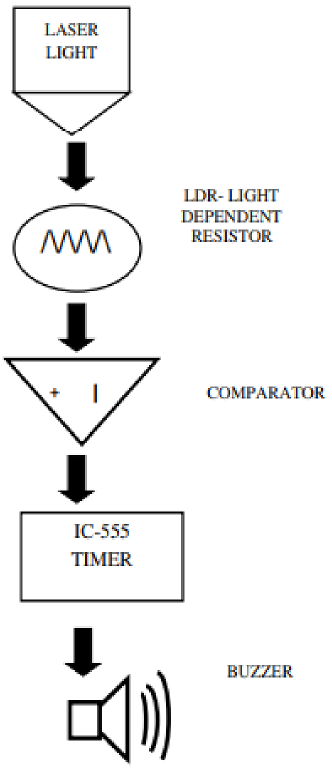

Figure. 1 Block diagram of Laser Security System

B. CIRCUIT DIAGRAM

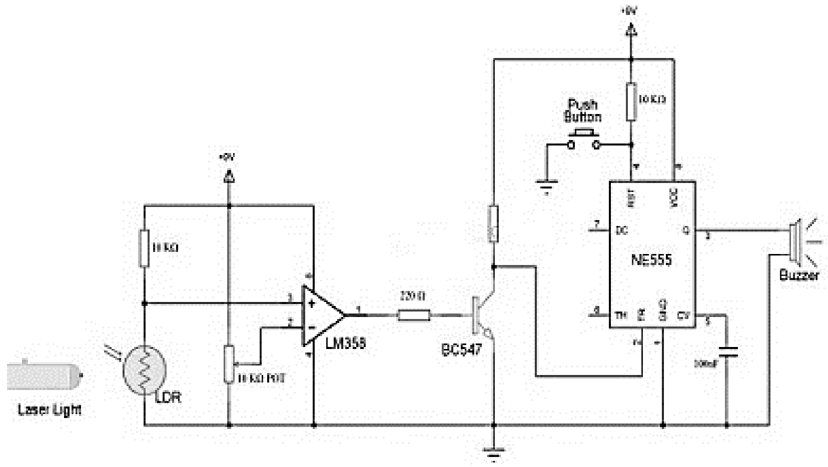

Figure.2 Circuit Diagram of Laser Home Automation System

A. COMPONENTS REQUIRED

Table-1: Components with Specifications

SL.NO.	NAME OF THE COMPONENT	SPECIFICATIO S	QUANTITY
1	Op – Amp IC	LM358	1
2	Timer IC	IC 555	1
3	LDR	--	1
4	Resistors	10 KΩ	3
		220Ω	1
5	Small Buzzer	--	1
6	Potentiometer	10 KΩ	1
7	NPN Transistor	BC547	1
8	Capacitor	100 nF	1
9	Push Button	--	1
10	Laser Pointer	--	1
11	9V Battery	--	1
12	Connecting Wires	--	--
13	Breadboard	--	1

B. COMPONENT DESCRIPTION

A laser figure.3 is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation. The term "laser" originated as an acronym for "light amplification by stimulated emission of radiation". A laser differs from other sources of light in that it emits light coherently. Spatial coherence allows a laser to be focused to a tight spot, enabling applications such as laser cutting and lithography. Spatial coherence also allows a laser beam to stay narrow over great distances (collimation), enabling applications such as laser pointers. Lasers can also have high temporal coherence, which allows them to emit light with a very narrow spectrum, i.e., they can emit a single color of light. Temporal coherence can be used to produce pulses of light as short as a femtosecond. In Table.1 components specifications and quantity has been mentioned for this proposed home security system.

Figure 3: LASER POINTER

LDR (Light Dependent Resistor):

A photo resistor or light-dependent resistor (LDR) (Figure 4) or photocell is a light-controlled variable resistor. The resistance of a photo resistor decreases with increasing incident light intensity; in other words, it exhibits photoconductivity. A photo resistor can be applied in light sensitive detector circuits, and light- and dark-activated switching circuits.

Figure 4: LDR

Photo resistors work based off of the principle of photoconductivity. Photoconductivity is an optical phenomenon in which the material's conductivity is increased when light is absorbed by the material. When light falls i.e. when the photons fall on the device, the electrons in the valence band of the semiconductor material are excited to the conduction band. These photons in the incident light should have energy greater than the band gap of the semiconductor material to make the electrons jump from the valence band to the conduction band. Hence when light having enough energy strikes on the device, more and more electrons are excited to the conduction band which results in a large number of charge carriers.

LED (Light Emitting Diode):

A light-emitting diode (LED) is a two-lead semiconductor light source. Like an ordinary diode, the LED diode works when it is forward biased. In this case, the n-type semiconductor is heavily doped than the p-type forming the p-n junction. When it is forward biased, the potential barrier gets reduced and the electrons and holes combine at the depletion layer (or active layer), light or photons are emitted or radiated in all directions. A typical figure blow showing light emission due electron-hole pair combining on forward biasing.

BUZZER:

A buzzer (Figure.6) or beeper is an audio signaling device, which may be mechanical, electromechanical, and piezoelectric. Typical uses of buzzers and beepers include alarm devices, timers and confirmation of user input such as a mouse click or keystroke. Early devices were based on an electromechanical system identical to an electric bell without the metal gong. Similarly, a relay may be connected to interrupt its own actuating current, causing the contacts to buzz. Often these units were anchored to a wall or ceiling to use it as a sounding board.

Figure 6: BUZZER

TRANSISTOR

A transistor is a semiconductor device used to amplify and switch electronic signals and electrical power. Transistor has many functions, such as detecting, rectifying, amplifying, switching, voltage stabilizing; signal modulating and so on. It is composed of semiconductor material with at least three terminals for connection to an external circuit. A voltage or current applied to one pair of the transistor's terminals changes the current through another pair of terminals. As a variable current switch, transistor can control the output current based on the input voltage. Because the controlled (output) power can be higher than the controlling (input) power, a transistor can amplify a signal. Today, some transistors are packaged individually, but many more are found embedded in integrated circuits.

RESISTOR

A resistor (Figure.8) is a passive two-terminal electrical component that implements electrical resistance as a circuit element. Resistors act to reduce current flow, and, at the same time, act to lower voltage levels within circuits. In electronic circuits resistors are used to limit current flow, to adjust signal levels, bias active elements, terminate transmission lines among other uses. High-power resistors that can dissipate many watts of electrical power as heat may be used as part of motor controls, in power distribution systems, or as test roads for generators. Fixed resistors have resistances that only change slightly with temperature, time or operating voltage.

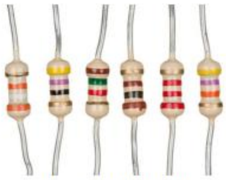

Figure 8: RESISTOR

CAPACITORS

Capacitors, Figure.9 are widely used in electronic circuits for blocking direct current while allowing alternating current to pass. In filter networks, they smooth the output of power supplies. In resonant circuits they tune radios to particular frequencies. In electric power transmission systems, they stabilize voltage and power flow.

Figure 9: CAPACITORS

BATTERY

An electric battery, figure.13 is a device consisting of two or more electrochemical cells that convert stored chemical energy into electrical energy. Each cell contains a positive terminal, or cathode, and a negative terminal, or anode. Electrolytes allow ions to move between the electrodes and terminals, which allows current to flow out of the battery to perform work. Primary (single-use or "disposable") batteries are used once and discarded; the electrode materials are irreversibly changed during discharge. Common examples are the alkaline battery used for flashlights and a multitude of portable device.

Figure.10 Battery 9V

TIMER

The 555 timer IC, Figure.11 is an integrated circuit (chip) used in a variety of timer, pulse generation, and oscillator applications. The 555 can be used to provide accurate time delays, as an oscillator, and as a flip-flop element. Derivatives provide two (556) or four (558) timing circuits in one package. In bistable mode, the 555 timer acts as a SR flip-flop. The trigger and reset inputs (pins 2 and 4 respectively on a 555) are held high via pull-up resistors while the threshold input (pin 6) is grounded. Thus configured, pulling the trigger momentarily to ground acts as a 'set' and transitions the output pin (pin 3) to VCC (high state). Pulling the reset input to ground acts as a 'reset' and transitions the output pin to ground (low state). No timing capacitors are required in a bistable configuration. Pin 7 (discharge) is left unconnected, or may be used as an open-collector output.

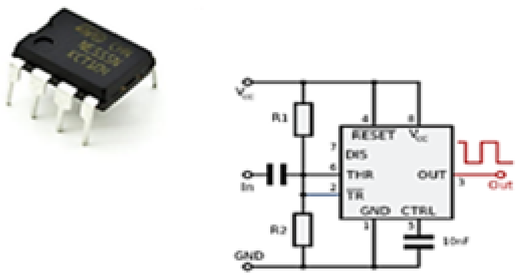

Figure.11-555 Timer IC

IC LM358:

In this project, the LM358, Figure.12 is used as a Comparator. The LM358 IC is a great, low power and easy to use dual channel op-amp IC. It is designed and introduced by national semiconductor. It consists of two internally frequency compensated, high gain, and independent op-amps.

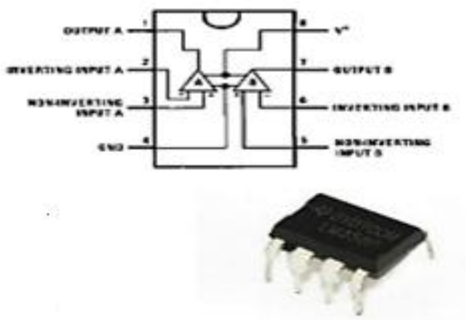

Figure.12-LM358

POTENTIOMETER:

A potentiometer, Figure.13 is a three-terminal resistor with a sliding or rotating contact that forms an adjustable voltage divider. If only two terminals are used, one end and the wiper, it acts as a variable resistor or rheostat. The potentiometer is a simple device used to measure the potentials (or compare electrical the e.g. of a cell).

Figure.13 Potentiometer

C. CIRCUIT DESIGN*:*

The design, Figure.14 of the laser security system circuit is very simple. Coming to the design of the circuit, first, the LDR and a 10 K Ω resistor are connected in series with the voltage divider and its output (common point) is connected to the pin 3 (non – inverting) of the Op- Amp IC LM358. For the inverting terminal (pin 2), connected the wiper of a 10 KΩ potentiometer (other two terminal of the POT are connected to VCC and GND). The 8th and 4th pin of Op-Amp IC LM358 are connected to the voltage divider and ground respectively. The output of the Op – Amp (Pin 1) is connected to the base of the transistor (BC547) through a resistor of 220 ohms. The trigger pin of 555 (Pin 2) is connected to the common point of 10 KΩ resistor and collector of transistor common point. The other end of resistor is given to voltage divider [7-10]. The emitter of the transistor is given to the ground the reset pin (pin 4) of the 555 is connected to VCC through a 10 KΩ resistor and a push button is connected between Pin 4 of 555 and GND. The non-inverting input (5th pin) is connected to ground through 100nano farad capacitor. A buzzer is connected to pin 3 of ic555 IC. The other end of buzzer is given to the ground the voltage divider (8th pin) of ic555 timer is given to voltage divider and the output pin (1st pin) is given to the ground.

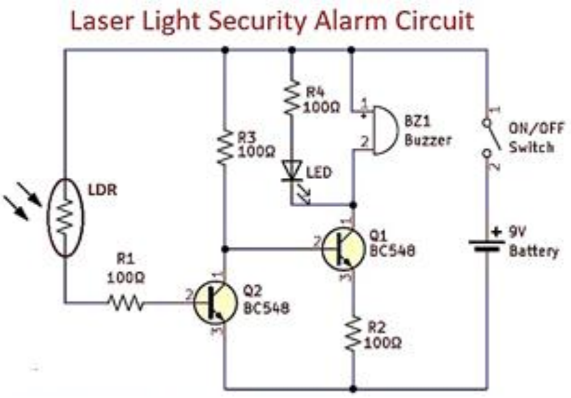

Figure.14 Lase Security Alarm System

II. Result obtained from proposed methodology

Here some key highlights mentioned from a Home Protection System scheme considered:

I. Deterrence: Visible security systems discourage potential intruders.

II. Early Detection: Sensors detect intrusions and trigger alarms.

III. Rapid Response: Alerts are sent to homeowners and monitoring services.

IV. Peace of Mind: Knowing your home is protected reduces anxiety.

V. Potential Insurance Discounts: Some insurers offer lower premiums for secured homes.

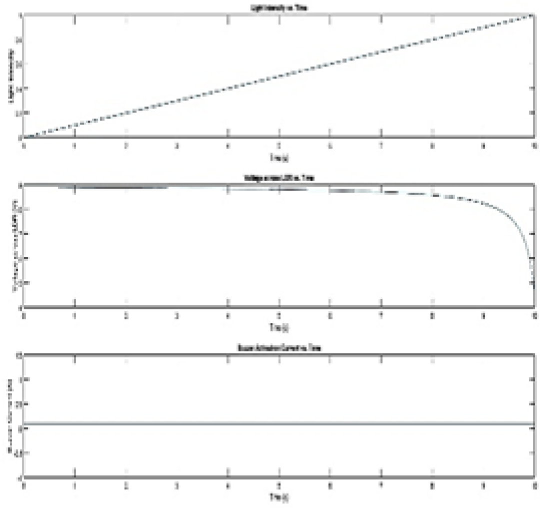

Figure.15 Characteristics of Light Intensity, Voltage Variation with Time

From Figure.15 Light intersity variation with time, Voltage across LDR and Current characteristics has been graphically obtained using online circuit simulator simulation.

IV. CONCLUSION

Laser security system provides us the security against any crime, theft in our day to day life and so people are installing them in order to stay safe, secure and sound. Various electronic security systems can be used at home and other important working places for security and safety purposes. It is a great opportunity and source of saving man power contributing no wastage of electricity.

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Modelling One Dimensional Heat Equation Using Feed Forward Neural Networks: A Comparative Study with Analytical Solutions

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ABSTRACT

This research paper presents the use of a feedforward neural network to solve heat conduction equation and compares its performance with the exact solution. We use an ANN to approximate heat distribution by learning spatial and temporal patterns from data generated by the explicit finite difference method. Levenberg-Marquardt algorithm (LMA) is used as optimization algorithm in MATLAB. Also surface and contour plots are developed which are used to demonstrate numerical solution of the heat equation and error function. In addition, the prediction is quantitative analyzed by comparison of the predicted real values and the exact solution by Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and R^2 value. The results illustrate that the ANN is an accurate and efficient alternative for solving ODEs when compared to traditional numerical methods.

Keywords: Feedforward Neural Network, Heat Equation, Machine Learning, Numerical Methods, Computational Modeling

I. INTRODUCTION

The heat conduction equation [1,14-15] is the most basic PDE used to describe the distribution of heat (or temperature) in a particular area with respect to time. It is very popular in many fields for simulating system behaviour because it is extremely simple to formulate. Typically, the heat equation is solved by various numerical techniques such as Finite Difference Methods (FDM)[11,13,15-16], Finite Element Methods (FEM)[13], and Finite Volume Methods (FVM)[15]. Though these techniques can easily provide solutions for dynamic processes at multiple scales, they usually require fine domain decomposition and are hence very expensive computationally when the domain is large or for long time simulations.

Among the alternatives to traditional methods, artificial neural networks have recently gained popularity. Because complex functions are well within the capability of approximation by ANNs, these entities may learn data characteristics and therefore offer an innovative approach. In this paper, a review was performed on various applications of ANN [1-3,6-7,12, 17-18] in heat conduction problems, particularly focusing on inverse and microscale heat transfer issues where it has proven effective. A new method for inverse heat conduction called Physics-Informed Neural Network was presented by Qian et al. [4] which improved accuracy due to the involvement of physical constraints. Bora et al. [5] applied ANNs to solve parabolic two-temperature microscale heat conduction in thin films under ultrashort-pulsed lasers, which by means of such lasers, as they indicate, sharp thermal modelling can be achieved. Tanuja et al [8] used ANNs to study thermal conductivity in porous fins, which again shows the applicability in geometries that are complex. Thander [9] has shown numerical efficiency through the use of the Levenberg-Marquardt algorithm in ANNs while solving the Poisson equation. Sun et al [10] used ANNs for predicting supercritical CO_2 transfer behaviour on heat transfer and recently CNNs were credited with analogous competence concerning conduction modelling by Tadeparti and Nandigana [13]. All these works mark a wide scope of ANN applicability concerning thermal analysis from inverse trouble to predictive modeling under divergent heat transfer activities.

This study follows the implementation of one-dimensional heat equation solution through a feedforward neural network which receives analytical solution validation through several plots. The performance evaluation of the network relies on three metrics including Mean Absolute Error (MAE), Root Mean Square Error (RMSE) and R-squared (R^2). Compare to traditional numerical methods, ANNs have a more efficient and promising numerical solution for partial differential equations which demonstrates machine learning potential in this application [6-7, 12].

Section II of this paper presents the domain decomposition of the partial differential equation, numerical scheme for approximate solution and the analytical solution of the PDE. A detailed description of the neural network is presented in Section III. The section IV analyses the numerical results with extensive detail. Final remarks along with research prospects toward future investigation comprise Section V and Section VI respectively.

II. THE HEAT CONDUCTION EQUATION

The heat conduction equation [19] within uniform area where $t \in [0, A_D]$, $x \in [0, B_D]$ is

$$\frac{\partial v}{\partial t} = \alpha \frac{\partial^2 v}{\partial x^2} \qquad (1)$$

Here $v(x,t)$ is temperature at (x,t) and α is thermal diffusivity.

We prescribe Dirichlet Boundary Conditions as, $v(0,t) = 0, v(1,t) = 0, \forall t \in (0, A_D)$ and

$v(x,0) = \sin \pi x, \ \forall x \in (0, B_D)$

For computational solution of Eq. (1), we have discretised the uniform domain into uniform grid points [11,13] where Δx and Δt are grid size along x and t directions respectively. Suppose (x_i, t_n) be a grid point in solution zone. Therefore $x_i = x_0 + i\Delta x, t_n = t_0 + n\Delta t$. We have considered (x_0, t_0) as (0,0). We have used parameter values as A_D=1, B_D=1, $\Delta x = 0.025$, $\Delta t = 0.025$

Approximate solution of this heat equation can be obtained using the **explicit finite difference method (FDM)**, with the following numerical scheme [20-21]

$$v_{i,n+1} = v_{i,n} + \alpha \frac{\Delta t}{\Delta x^2}\left[v_{i+1,n} - v_{i,n} + v_{i-1,n}\right]$$

Order of this scheme is 2nd order in space and first order in time.

Here Courant–Friedrichs–Lewy (CFL) condition is $\left\| \alpha \frac{\Delta t}{\Delta x^2} \right\| \le 1$ [19].

The analytical solution of the Eq. (1) is

$$v_e = e^{-\alpha\pi^2 t} \sin \pi x \, .$$

We have used this analytical solution to compute the error function($\|v_e - v_a\|_2$) computationally in L_2 space. Numerical solution of Eq.(1) using ANN is v_a .

III. Feed-Forward Neural Network in MATLAB

MATLAB toolbox Artificial Neural Networks provides users with a complete framework to construct and train neural systems that now falls under the Deep Learning Toolbox [9, 12, 22]. Data preparation becomes a necessary initial step through which users need to use built-in functions such as *mapminmax* and *zscore* to normalize their datasets. Users need to select the network type between *feedforwardnet* for feedforward architectures or *narnet/timedelaynet* for temporal pattern evaluation. The *dividerand* or *divideblock* functions separate data into certain groups for training and validation and testing purposes. Initiating the network requires either the Levenberg-Marquardt algorithm called *trainlm* or the scaled conjugate gradient algorithm referred to as *trainscg* for training purposes. Performance monitoring through mean squared error (MSE) and regression plots and performance curves happens during training operations. After training the network it needs evaluation with new data to verify proper fit between data points. The software enables users to visualize weights and observe error histograms together with confusion matrices during classification operations. Just like previous steps the trained network could be saved and simulated using the *sim* function and can be used in Simulink models and real-time systems. MATLAB delivers an efficient operation flow that enables researchers to use it effectively for ANN modeling and applications development.

In this study, the ANN is trained using numerical data generated from the explicit Finite Difference Method (FDM), which discretizes the heat equation over a spatial domain of $B = 1$ with 40 grid points and a temporal domain of $t_{\max} = 0.6$ with 24 time steps. The numerical solution using ANN is computed with a thermal diffusivity parameter $\alpha = 1$ and $\Delta x = 0.025$, $\Delta t = 0.025$ satisfying the Courant–Friedrichs–Lewy (CFL) condition to ensure stability. An ANN utilizes feedforward structure that includes two middle layers possessing 25 tansig neurons before using purelin activation functions at the output layer. A total of 1000 epochs from Bayesian Regularization (trainbr) serve for training while maintaining a performance goal of to strike an accurate and generalized result. The ANN reaches temperature distribution approximation through its ability to connect mapped spatial and temporal coordinates to the temperature values obtained through FDM. After the neuro computing network finishes its training process it produces a single continuous expression of heat equation solutions which cuts processing costs while permitting estimations outside FDM's limited grid points. The ANN solution accuracy is measured by analyzing Mean Squared Error, Mean Absolute Error along with the coefficient of determination for statistical metrics. Additionally, visual surface plot and contour map comparisons with numerical and exact solutions are used for evaluation.

IV. ANN Architecture and Training Methodology

Training ANN requires weight and bias adjustments from input data in order to decrease output discrepancies compared to target results. An extensive review of neural networks can be found in [1-3,9,12,22]. Multi-layer ANN requires Backpropagation algorithm to apply successive weight and bias updates during training. An ANN's precision level depends strongly on accessing enough training data to work with.

The training dataset is regularly split into three distinct groups referred to as training data validation data and testing data. Separately the three divisions evaluate the training effectiveness. The assessment method provides complete results for the entire data set while allowing researchers to compare different training techniques and ANN configurations.

The MATLAB platform allows us to create a large 100X100 sample dataset for handling heat conduction equation. The training stage uses three separate groups of samples totaling 100X100 in which seventy percent gets used for training and fifteen percent each serves for validating and testing purposes. ANN training occurs through implementation of the Levenberg-Marquardt algorithm. The method is applied to run three training cycles for each network configuration which consisted of 1000 epochs [14]. Here Courant–Friedrichs–Lewy (CFL) value is 0.49.

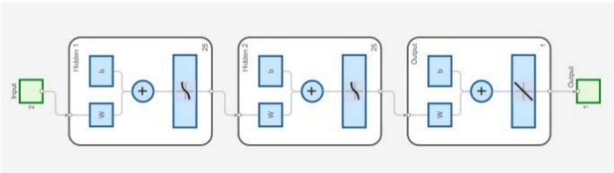

Figure 1: ANN Architecture with Two Hidden Layers of 25 Neurons Each

ANN architecture created for the computational solution of (1) is depicted in Figure 1. The surface and contour plots, respectively, in Figures 2 and 3 illustrate computational solution for the heat equation using current approach.

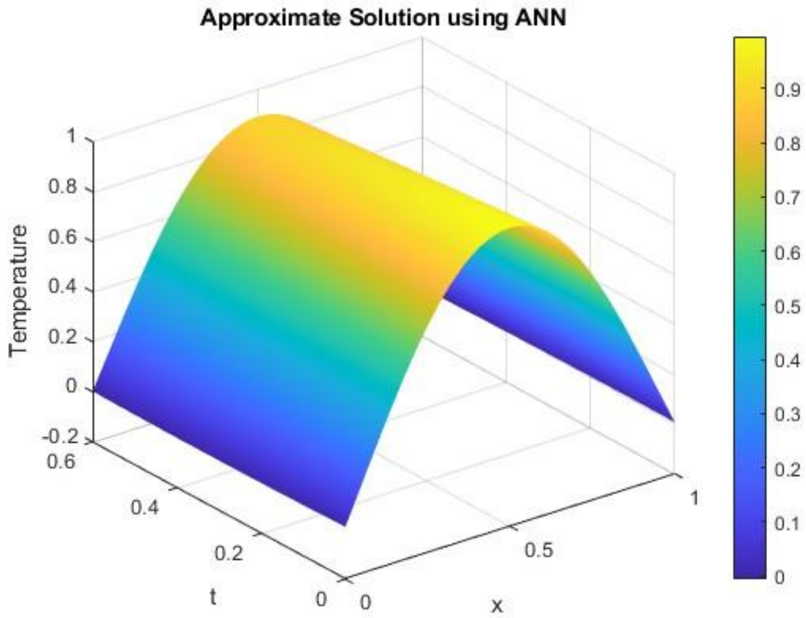

Figure 2: 3D plot of solution of heat equation

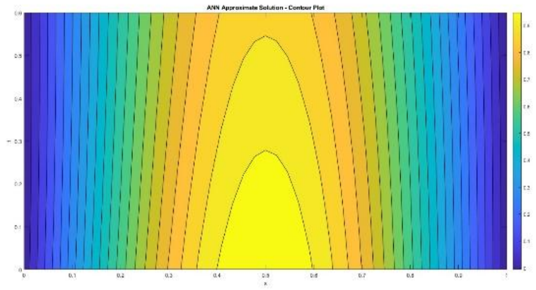

Figure 3: 2D Contour Map of heat equation

Here Levenberg-Marquardt algorithm (LMA) training performance results are shown in Figures 4 through 7. The performance curve in Figure 4 shows that as epoch number rises, the MSE lowers. The test set error and the validation set error exhibit same type of patterns, which is notable. Up to epoch 1000, no significant overfitting problem is seen for this ANN model. MSE drops to an exceptionally low value of 6.2658e-06 at epoch 14. The gradient plot in Figure 5 provides information about the optimization methods used to achieve global solutions.

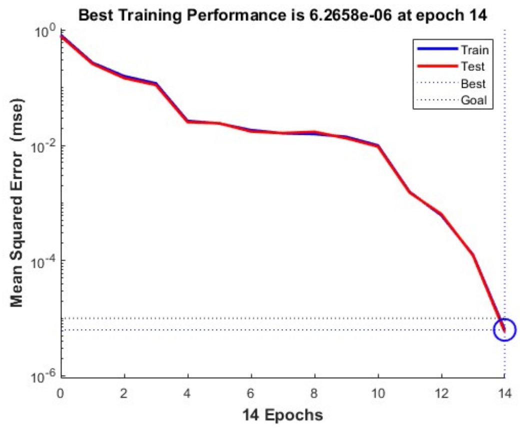

Figure 4: MSE Values Across Various Training Epochs During Optimization.

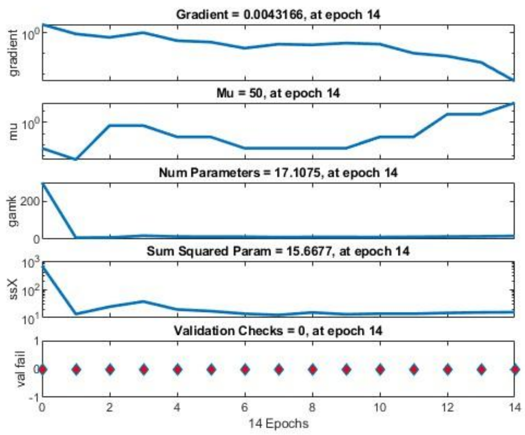

Figure 5: Training State of the Neural Network Observed at Various Epochs During the Learning Process

Table 1: Statistical Performance Metrics after epoch 14	
Metrics	Values
Mean Squared Error (MSE)	0.0001524
Mean Absolute Error (MAE)	0.0083761
R-squared (R^2)	0.9983472

The statistics in Table 1 present a full view of the ANN's performance. As the MSE and MAE values are low, it can confidently be said that the ANN 0estimates the numerical FDM solution with very little deviation. Since the R-squared (R^2) is closest to 1, this indicates that there is a very strong correlation, and underlines the fact that the ANN is modelling the dynamics of the heat conduction problem correctly with the given parameters. All this evidence confirms validity and accuracy of any ANN-based approach.

The error histogram for ANN model is split into 20 bins in Figure 6. The yellow line in this picture represents zero error, and we can see that 250 occurrences of these zero mistakes occur during the training period. Now the relationship between expected output values and measured target values is shown individually for steps of training and testing in Figure 7. Here the R values in each of the three sub-figures show that the ANN model produces positive outcomes. Notably, Figure 7 shows a robust match with slope and intercept values that are about 1 and 0, respectively, for all examples. Additionally, as shown in Figure 7 for all cases, the R-value continuously about 100%, indicating exceptional effectiveness for whole data.

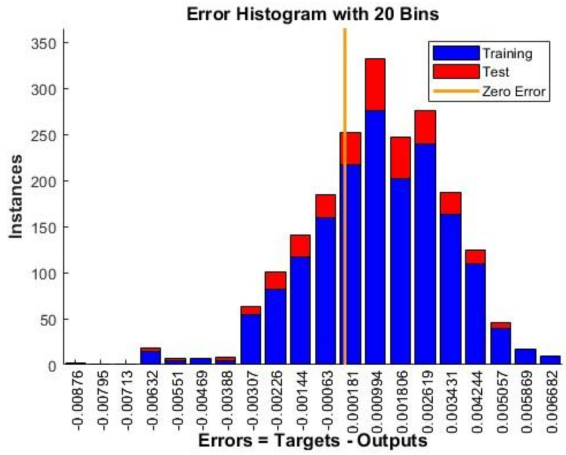

Figure 6: Histogram of Neural Network Training Errors Using 20 Bins to Illustrate Error Distribution

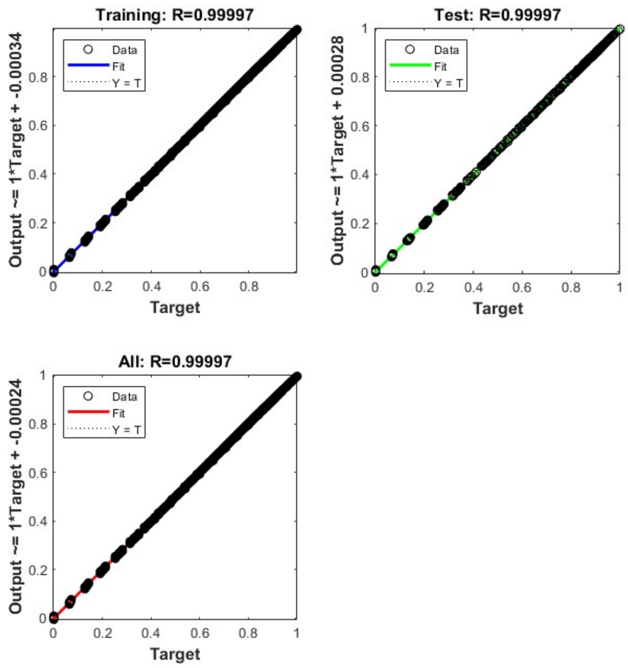

Figure 7: Regression Analysis of Neural Network Training Results Showing the Relationship Between Predicted and Actual Values

Plotting the difference between the analytical and computed solutions allows us to determine if the mistake is within a certain order 10^{-8}.

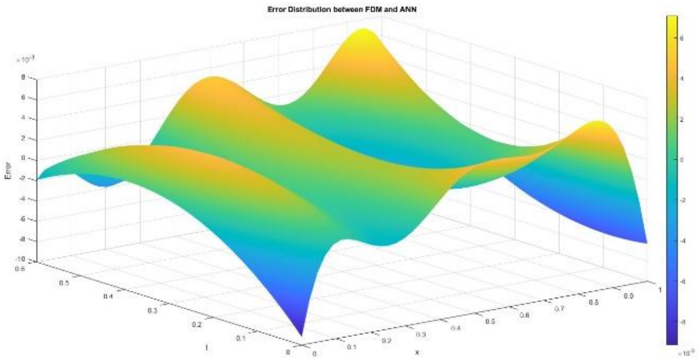

Figure 8: 3D Surface of Error Function

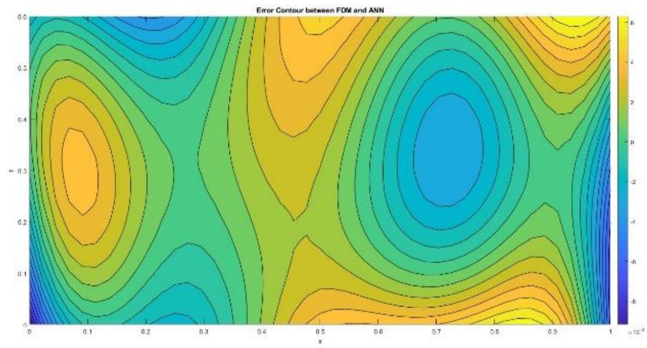

Figure 9: Contour of error function

3D and 2D plots of error function of one dimensional heat conduction equation is shown in Figures 8 and 9. By contrasting the numerical solution derived from the present method with exact solution of the heat equation, this error function is calculated in L2 space.

A similar network is used by Liu et al. [22] for ANN-based radial basis function to get a computational solution for PDEs where the training data includes the radial distances between the boundary points of the solution domain and external fictional sources. This method works perfectly using Dirichlet boundary conditions. However, a limitation of our technique is that the solution domain must be discretized, which is different from what Liu et al. [22] demand. Also our approach has limitation in its ability to handle PDEs with intricate geometries, where it is not practical to use uniform grids with a consistent ratio and size.

V. CONCLUSION

In this research work, an ANN is trained to approximate solution to the one-dimensional transient heat conduction equation using numerical data generated through an explicit finite difference scheme. The network is configured with two hidden layers with 25 neurons each, and is able to successfully learn the complex spatial and temporal behavior implicit throughout the dataset. The results of the ANN are assessed using several statistical measures which indicates a high correlation in the ANN predictions and the corresponding numerical results from FDM. Also Surface plots, contour maps, and element histograms are developed for the ANN predictions for verifying computational efficiency and flexibility in solving heat conduction problems. Overall, this work demonstrates the promise of using neural networks for heat conduction as a viable alternative to traditional numerical methods.

VI. FUTURE PLAN

Future investigations will focus on increasing the accuracy of ANNs by improving the network architecture, along with the numerical training data. Extending the research to multi-dimensional heat conduction and spatially-varying thermal properties, would improve the generalizability of the model. Additional work could also be devoted to couple the ANN with Physics-Informed Neural Networks (PINNs) for other scientific applications to validate the framework.

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Corrosion Behaviour of Hastelloy C276 for Industrial Applications

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ABSTRACT

Hastelloy C-276, a nickel-molybdenum-chromium alloy with added iron and tungsten, is renowned for its exceptional resistance to a wide range of severe environments, including strong oxidizing and reducing agents. This paper comprehensively examines the chemical composition, microstructure, mechanical properties, and corrosion resistance of Hastelloy C-276, with a focus on its applications in the chemical processing, marine, and energy industries. The alloy's superior performance in aggressive media such as hydrochloric acid, sulfuric acid, and chloride-containing environments is analyzed in the context of its metallurgical stability and passivation behavior. Furthermore, this research identifies areas where existing research is lacking, such as long-term performance in real-world environments, environmental impact and sustainability, lack of standardized testing across studies, challenges related to fabrication cost, and potential environmental degradation mechanisms. This paper aims to provide a consolidated understanding of Hastelloy C-276's capabilities and limitations, offering guidance for its optimal utilization in critical industrial applications.

Keywords: Hastelloy C276, corrosion resistance, microstructure, degradation, fabrication

I. INTRODUCTION

The superior corrosion resistance of Hastelloy C-276 can be attributed to its unique chemical composition. The high nickel content provides excellent resistance to chloride-induced stress corrosion cracking, while molybdenum enhances resistance to pitting and crevice corrosion. Chromium improves the alloy's ability to withstand oxidizing agents, and tungsten further enhances its resistance to localized attack. This combination allows Hastelloy C-276 to perform effectively in environments that would quickly degrade other materials, such as concentrated hydrochloric acid, sulfuric acid, and chlorine-containing solutions. Hastelloy C276 is anticipated to be appropriate for use as a pump impeller at high temperatures in 35% HCl [1].Despite its proven effectiveness, on-going research continues to explore the alloy's behaviour under complex environmental conditions and its performance in newer manufacturing methods, such as additive manufacturing. Additionally, understanding the mechanisms behind localized corrosion and its interaction with microstructural features remains an area of active investigation. This review aims to consolidate existing knowledge on the corrosion resistance of Hastelloy C-276 while highlighting recent advances, challenges, and future research directions.

II. OVERVIEW ON HASTELLOY-C276

In this section composition (Table 1), mechanical properties (Table 2) and physical properties (Table 3) of selected alloy is studied and discussed. Effect of temperature on tensile strength (Fig. 1) and compressive strength is studied (Fig. 2). It is observed that this superalloy can retain its strength upto 700 ˚C.

Table 1: Compositional ranges of alloy elements in Hastelloy C276 [2]

Element	Composition	Role In Alloy
Nickel (Ni)	Balance (~57%)	Gives general corrosion resistance and fortifies and toughens.
Molybdenum (Mo)	15.0 – 17.0	It improves resistance to stress corrosion cracking, pitting, and crevice corrosion.
Chromium (Cr)	14.5 – 16.5	It enhances resistance to corrosion and oxidation, particularly in oxidizing and acidic environments.
Iron (Fe)	4.0 – 7.0	Increases the alloy's strength and stability.
Cobalt (Co)	≤ 2.5	Minimal impact on corrosion characteristics; naturally occurring as an impurity.
Tungsten (W)	3.0 – 4.5	Improves strength and corrosion resistance at elevated temperatures.
Manganese (Mn)	≤ 1.0	Enhances mechanical qualities and facilitates deoxidation while treating alloys.
Vanadium (V)	≤ 0.35	Increases durability and strength.
Silicon (Si)	≤ 0.08	Enhances mechanical qualities and regulates oxidation.
Carbon (C)	≤ 0.01	Low carbon content reduces inter-granular corrosion by minimizing carbide precipitation.
Phosphorus (P)	≤ 0.04	Kept low to preserve ductility and avoid embrittlement.
Sulfur (S)	≤ 0.03	Low concentration enhances weld-ability and inhibits hot cracking.

Table 2: Physical Properties of Hastelloy C276 [2]

Property	Value	Description
Density	8.89 g/cm³ (0.321 lb/in³)	Reveals the unit volume mass, which is relatively high due to the composition of nickel and molybdenum.
Melting Range	1325 – 1370°C (2417 – 2498°F)	Good thermal stability and resistance to high-temperature oxidation are made possible by the wide range.
Thermal Conductivity	10.2 W/m·K (at	Moderate heat conductivity, adequate for heat

	24°C)	exchanger applications but less than steels.
Specific Heat Capacity	427 J/kg·K (at 24°C)	Shows the capacity to absorb heat, which is helpful for thermal cycling applications.
Electrical Resistivity	1.27 µΩ·m (at 24°C)	Because of its high resistivity, it can be used in electrical applications where corrosion resistance is necessary.
Magnetism	Non-magnetic	It is appropriate for uses requiring non-magnetic characteristics.
Young's Modulus)	205 GPa (29.7 × 10^3 ksi)	Ensures strong structural stability by measuring the stiffness of the material.
Poisson's Ratio	0.30	Describes the behavior of elastic deformation under stress.

Table 3: Mechanical Properties of Hastelloy C276 [2]

Property	Value	Description
Tensile Strength (Ultimate Tensile Strength, UTS)	790 MPa (115 ksi)	Refers to the highest stress the material can tolerate before it fails.
Yield Strength (0.2% Offset)	355 MPa (52 ksi)	The material begins to undergo plastic deformation.
Elongation (%)	40%	Measures ductility, indicating ability to stretch before fracture.
Hardness (Brinell Hardness, HB)	230 max	Moderate hardness, ensuring good wear resistance without brittleness.
Hardness (Rockwell B, HRB)	80 max	Indicates relative hardness compared to other metal alloys.
Impact Toughness	Excellent	Provides high resistance to fracture under sudden loading.
Fatigue Strength	~275 MPa (40 ksi) (at 10^7 cycles)	Ensures long-term durability under cyclic loading conditions.
Creep Resistance	High	Maintains strength at elevated temperatures under constant stress.

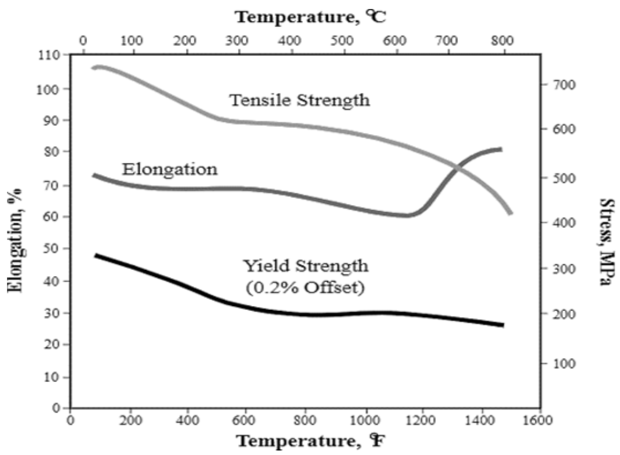

Fig. 1: Tensile properties of Hastelloy C276

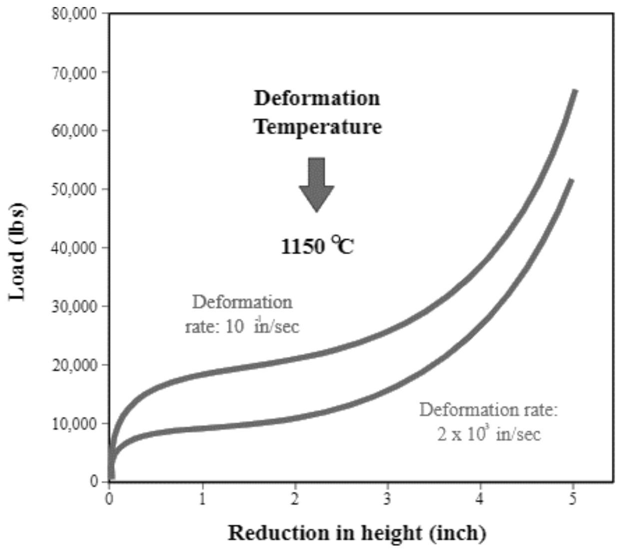

Fig. 2: Load deformation curves during compression of Hastelloy C276

A. Microstructural Features of Hastelloy C276

The microstructure of Hastelloy C276 is highly engineered to deliver superior mechanical and thermal properties. The key phases and their roles are outlined below:

1. Single-Phase FCC Structure: The alloy primarily consists of a face-centered cubic (FCC) austenitic matrix due to its high nickel content [3]. This structure provides excellent toughness, ductility, and resistance to stress corrosion cracking.

2. Precipitate-Free Structure in Solution-Annealed Condition: In the solution-annealed state (typically at 1100°C–1150°C followed by rapid quenching), Hastelloy C276 remains free from carbide and intermetallic phase precipitates [4]. This prevents grain boundary sensitization, maintaining corrosion resistance in aggressive environments.

3. Secondary Phase Precipitates (at Elevated Temperatures): When exposed to prolonged high-temperature service or improper heat treatment, secondary phases such as M_6C (molybdenum-rich carbides) and σ (sigma) phase may form at grain boundaries [5]. These phases can reduce corrosion resistance and mechanical strength, making controlled heat treatment essential.

4. Grain Size Variation: The grain size of Hastelloy C276 depends on the processing conditions. Fine grains improve strength and toughness, while coarser grains may slightly enhance high-temperature stability [6].

B. Corrosive Feature of Hastelloy C276

Corrosion is the irreversible degradation or breakdown of a material due to chemical or electrochemical reactions with its environment. This is the destruction of materials through mechanisms other than direct mechanical action. It constitutes one of the greatest concerns in industries such as aerospace, chemical processing, energy, and marine engineering, in which materials are constantly exposed to aggressive conditions in the environment [7]. Apart from the loss of structural integrity, corrosion causes great economic losses and further hazards to safety.

Since the beginning of civilization, corrosion has been an age-old phenomenon. The metal world has been crucial in the progress of mankind. Evidence of corrosion was found from ancient times, as degradation was visible on the iron and bronze tools and artifacts when exposed for a long period of time under environmental conditions [8].

Fig. 3: Effects of Corrosion

Hastelloy C276 offers excellent resistance to a wide range of corrosive environments, strong oxidizing and reducing acids. It is an ideal material for chemical processing industries [9]. It has high-temperature stability and retains its mechanical properties even at elevated temperatures. Its main application is used in heat exchangers, boilers, and reactors where high-temperature stability is required [9]. Unlike some other corrosion-resistant alloys, Hastelloy C276 can be easily welded without the risk of carbide precipitation, reducing intergranular corrosion in welded structures. It has longevity and Cost-Effectiveness. Durability and corrosion resistance of Hastelloy C276 reduces maintenance and replacement costs, making it a cost-effective choice for long-term industrial applications. Resistance to Pitting and Crevice Corrosion is good. The presence of molybdenum (15-17%) gives significant protection against localized corrosion like pitting and crevice corrosion that is typical in chloride-rich environments, including those found at sea and chemical plants.

There are various types of corrosions like:

1. *Pitting Corrosion:* This is an extremely limited mode of corrosion that develops in limited pits on the material's surface area. It usually happens when a securing oxide coating on the material is broken or breach, revealing the fundamental metal to aggressive ions like chlorides.
2. *Crevice Corrosion:* This happens in enclosed spaces where oxygen levels are restricted, like in intersections, gaskets, and under deposits. These areas form microenvironments accompanying lower pH and greater chloride concentrations, expediting localized corrosion [10].
3. *Uniform Corrosion:* This takes place evenly across the surface of a material when it reacts identically accompanying its climate. It frequently results from exposure to oxygen, moisture, or acidic surroundings. While it mainly progresses at a stable rate, uniform corrosion can bring about material breakdown over period if not controlled [11].
4. *Galvanic Corrosion:* This continues when two opposing metals are in contact electrically in the form of an electrolyte, such as water or humidity. The more anodic alloy corrodes preferred, while the cathodic metal remnants secured.
5. *Inter-granular Corrosion:* This happens along the grain perimeters of a material by reason of the exhaustion of defensive factors like chromium in certain zones. Solutions contain suitable heat treatment, stabilization accompanying materials like titanium or niobium, and the use of reduced-carbon grades of alloys.
6. *Stress Corrosion Cracking (SCC):* This phenomenon occurs when tensile stress interacts with a corrosive environment, resulting in the formation of cracks.

7. *Erosion:* This type of corrosion happens when the flow of a fluid, such as water or gas, accelerates the removal of the protective coating from a material, exposing it to increased corrosion [12].
8. *High-Temperature Corrosion:* This occurs when materials react with gases like oxygen, sulfur, or carbon dioxide at elevated temperatures. Common processes of high-temperature corrosion, including oxidation, sulfidation, and carburization, damage materials found in furnaces, gas turbines, and power generation facilities.

The corrosion occurs because of the natural tendency for most metals to return to their natural state; like, iron in the presence of moist air will revert to its bare state, iron oxide. Metal can be corroded through direct reaction of metal with chemicals and electro chemical reaction. The driving force that form metals deteriorate is an unrefined series of their momentary survival in the metallic form. Thermodynamically, corrosion is the strength of the metal to regress to compounds that are more durable, that is, present in the nature at first [13]. J. M. West in 1986 resorted to the combined-potential hypothesis that exists of two clear theories:

Any electrochemical reaction maybe divided into two or more partial oxidation and reduction reactions.

This implies that the overall rate of oxidation and the total rate of reduction must be identical throughout the corrosion of an electrically isolated metal sample [14]. The most significant type of corrosion classification is electrochemical corrosion, as illustrated in Fig. 4. Before electrochemical corrosion may occur, four requirements must be met:

• A cathode is required, as is something that corrodes (the metal anodes).

• A constant conductive liquid route (electrolyte, typically liquid, condensate, salts, and other contaminants) is required.

• In bolted or riveted connections, this conductor typically takes the shape of metal-to-metal contact.

• The rates of reduction and oxidation reactions may be equivalent [14, 15].

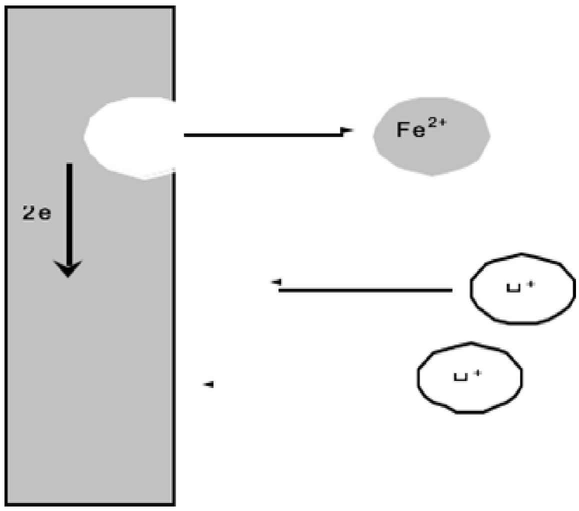

Fig. 4: Simple model describing the electrochemical nature of corrosion processes

Figure 5 Shows that, understanding the fundamentals of corrosion and removing any one factor will prevent corrosion. The current cannot flow if the metal's surface has an intact (optimal) covering that stops the electrolyte from joining the cathode and anode. Therefore, as long as the coating remains functional, corrosion won't proceed.

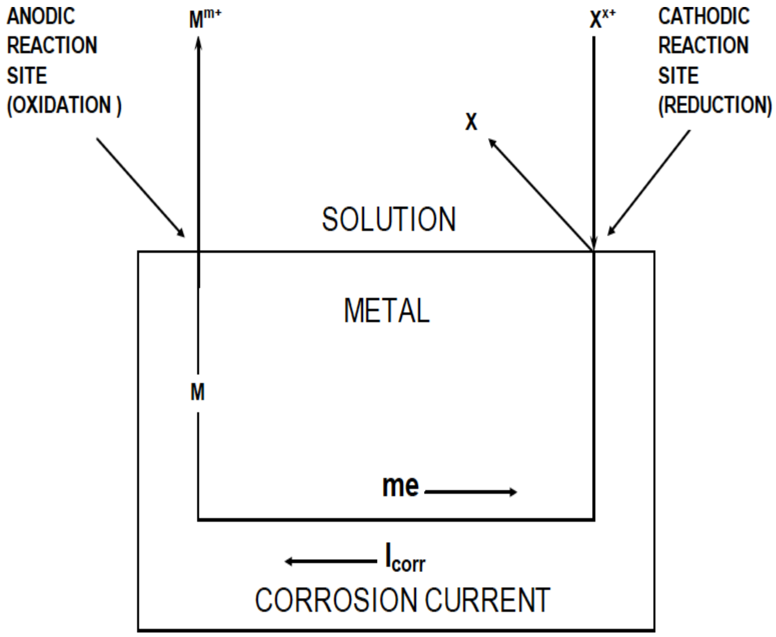

Fig. 5: The basic corrosion process

III. CORROSION IN HIGH-TEMPERATURE AND AQUEOUS ENVIRONMENTS

Investigation regarding the corrosion of Hastelloy C-276 in high temperature water environments [16] reported by Zhang and Tang during 2009. Their finding showed that even though the critical factor is found to be oxide film formation along with chromium as well as nickel oxides present in it protects the material a lot, then also at extreme temperatures, more exposure causes such film degradation allowing localized corrosion also.

Ghule and Chandramohan in 2022 [17] continued to study the corrosion resistance of Hastelloy C-276 in supercritical water oxidation conditions. Oxidation rates at supercritical conditions were accelerated due to the breakdown of passive films resulting in surface roughening and pitting. Guo et. al. (2022) [18] studied the behavior of pitting corrosion of Hastelloy C-276 in chloride-containing environments. Their study exposed that chloride ions attacked the passive layer aggressively, and pits initiate. In addition, molybdenum in the alloy composition strengthens by stabilizing the passive film. Kundalgurki (1992) [19] studied stress corrosion cracking in acid conditions, with particular interest in sulfuric acid solutions. Their results indicated that SCC was most active at grain boundaries where strain and environmental interaction would tend to facilitate crack growth.

Kim et.al. (2009) [20] explored the corrosion behavior of Hastelloy C-276 in sulphuric acid at many ranges of temperatures. The researchers concluded that in high temperature ranges, the rate of corrosion becomes higher because the dissolution of the passive layer enhances. Fan et. al. (2021) [21] studied its behavior in hydrochloric acid solutions and noted that Hastelloy C-276 maintains excellent resistance, although the prolonged exposure causes slight surface degradation due to selective dissolution of alloying elements. Ghosh et.al (2005) [22] have studied electrochemical parameters in phosphoric acid environments. The findings of the research indicated that the anodic dissolution rates and passivation behavior are significantly influenced by solution concentration and applied potentials.

IV. CORROSION IN SPECIALIZED ENVIRONMENTS

1. Marine Environments: Laura et.al. (2011) [23] showed that sulfate- reducing bacteria cause the MIC in seawater conditions, which means it causes localized attack and pitting.
2. Molten Salts: Gervasio et.al. (2015) [24] examined corrosion behavior in molten salt environments, finding that high-temperature exposure causes inter-granular attack and selective element depletion.
3. Flue Gas Desulfurization: Beavers (2002) [25] confirmed its high resistance in flue gas desulfurization systems, where exposure to sulfates and chlorides occurs.

Future work could be focused on tailoring heat treatment duration and other schedules to maximize corrosion resistance. Better characterization techniques, involving XRD, and EBSD, help in understanding phase transformations and stability at the microstructural level in detail.

V. RESEARCH GAPS AND CHALLENGES

Despite the well-established corrosion resistance and mechanical strength of Hastelloy C-276, several critical gaps remain in the current body of research, particularly concerning its long-term behavior and broader industrial applicability.

A. Long-Term Performance in Real-World Environments

Most corrosion studies on Hastelloy C-276 are conducted under controlled laboratory conditions, which do not always reflect the complexity of service environments. There is a lack of long-term field data that captures the alloy's performance over extended periods, particularly in dynamic, multi-variable environments such as offshore, chemical processing, and geothermal systems. Real-world degradation mechanisms, including fluctuating temperatures, mixed media, and microbial influence, remain insufficiently explored. [26]

B. Environmental Impact and Sustainability

While Hastelloy C-276 offers excellent durability, its environmental footprint has not been thoroughly assessed. The high energy consumption during its production, the mining of rare alloying elements (e.g., molybdenum, tungsten), and limited recycling studies raise concerns regarding sustainability. Additionally, end-of-life treatment and lifecycle analysis of the alloy are scarcely documented in literature, indicating a need for environmentally responsible innovation. [27]

C. Lack of Standardized Testing Across Studies

Variability in corrosion test methods—such as differing concentrations, temperatures, durations, and electrochemical techniques—limits the comparability of results across different studies. This inconsistency makes it challenging to establish universally accepted performance benchmarks and hinders the development of comprehensive material selection guidelines for industry professionals [27].

D. Fabrication Cost and Practical Challenges

The high cost of raw materials and complex fabrication processes, including machining and welding, pose significant challenges to the widespread adoption of Hastelloy C-276. Although the alloy is weldable, controlling microstructural integrity in heat-affected zones remains critical, as improper welding can compromise corrosion resistance. Cost-effective manufacturing and joining techniques remain underdeveloped areas [28].

E. Environmental Degradation Mechanisms

Although Hastelloy C-276 is designed to withstand harsh environments, it is not entirely immune to localized corrosion phenomena such as pitting, crevice corrosion, and inter-granular attack under certain conditions. Furthermore, synergistic effects involving mechanical loading, thermal cycling, and corrosive exposure are not fully understood. Advanced characterization methods and modeling are needed to predict degradation mechanisms more accurately in service [27].

Table 4: Optimal Utilization of Hastelloy C-276 in Key Industries [29]

Industry	Application Area	Advantages Of Hastealloy
Chemical Processing	Reactors, Heat exchangers, Columns, Absorbers	Resists strong acids (HCl, H_2SO_4), Handles mixed chemical environments.
Pollution Control / FGD	Scrubbers, Ducting, Mist eliminators	Excellent in acidic, chloride-rich gases, long service life under exposure.
Marine & Offshore	Pumps, Valves, Seawater piping, Heat exchanger	High resilience to pitting and corrosion in seawater crevices.
Pharmaceutical & Food	Bioreactors Sanitary pipes Mixing vessels	Clean ability, Resistant to cleaning chemicals, Biocompatible.
Nuclear & Energy	Fuel reprocessing units, Waste containers, High-temp exchangers.	Radiation stability, Corrosion resistance at high temperatures.
Emerging Technologies	Green hydrogen systems, Geothermal plants,	Handles harsh fluids, Stable under variable pressure and temperature.

VI. CONCLUSIONS

A. *Excellent Corrosion Resistance:* - Hastelloy C276 offers excellent resistance to a wide range of corrosive environments, strong oxidizing and reducing acids. For industries that process chemicals, it is the perfect material.

B. *Resistance to Pitting and Crevice Corrosion:-The greater content of molybdenum (15-17%) gives significant protection against localized corrosion like pitting and crevice corrosion that is typical in chloride-rich environments, including those found at sea and chemical plants.*

C. *High-Temperature Stability:-The alloy retains its mechanical properties even at elevated temperatures and is used in heat exchangers, boilers, and reactors where high-temperature stability is required.*

D. *Excellent Weld-ability:-Unlike some other corrosion-resistant alloys, Hastelloy C276 can be easily welded without the risk of carbide precipitation, reducing intergranular corrosion in welded structures.*

E. *Longevity and Cost-Effectiveness:-The durability and corrosion resistance of Hastelloy C276 reduce maintenance and replacement costs, making it a cost-effective choice for long-term industrial applications.*

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Alcohol Additives in Biodiesel : Type, Properties, And Their Effects: Review

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ABSTRACT

Over time the increasing energy demand and growing environmental problems have driven the development of biodiesel as a potential alternative to conventional diesel fuel. Biodiesel is produced via transesterification, derived from vegetable oils and animal fats. Biodiesel has several advantages, including biodegradability, non-toxicity, and high flash point. However, the higher density, viscosity and low energy content of biodiesel, when contrasted with that of diesel, can cause incomplete combustion, poor atomization and increase specific fuel consumption, according to the present study researchers have explored the use of alcohol additives (ethanol, methanol, butanol and pentanol) in biodiesel-diesel blends. It has been found that oxygen-rich compounds help the atomization of biofuels. It reduces viscosity and density, improves combustion efficiency, and contributes to the reduction of pollutants such as NOx, CO, and HC. Other alcohols higher than the alcohol concentration (butanol and pentanol, for example) have interest as they have excellent properties. Studies on the effects of alcohol additives on brake thermal efficiency have indicated that using alcohol additives in biodiesel blends significantly improved the thermal efficiency of brakes, decreased brake specific fuel consumption, and increased emission profiles. However, the addition of alcohols can increase the variability of combustion due to their volatility and ignition characteristics. In this paper, a study will be performed to analyse biodiesel production methods, properties, types of alcohol additives, and their effects on biodiesel fuel characteristics.

Key words: Biodiesel; Transesterification; Alcohol additives; Brake thermal efficiency; Brake specific fuel consumption; Emissions

I. INTRODUCTION

The increasingworldwide demand for energy, resulting from industrial expansion, the need for transportation, and the growth of the population, has led to concerns over the depletion of fossil fuel reserves and the related environmental damage. Diesel engines are particularly responsible for greenhouse gas (GHG) emissions and urban air pollution due to their widespread use in the transport and manufacturing sectors [1][5].

To solve this problem, biodiesel has been developed as a potential replacementfor conventional diesel. Biodiesel derived from renewable sources such as animal fats and vegetable oils by the process of transesterification,one of the key advantages of that biodiesel is biodegradable, non-toxic in nature, and has a relatively high flash point which makes it safer to handle [4][3]. Standards like EN14214 and ASTM D6751 provide guidelinesfor the quality and usability of biodiesel in internal combustion engines with minimum or no modification [4].

However, compared to conventional diesel, biodiesel has a higher density and viscosity and a lower energy content. This can result in incomplete combustion, poor atomization, and higher specific fuel consumption, particularly at high blend ratios [2][6][7]. To face these issues, researchers have studied the use of alcohol additiveslike ethanol, methanol, butanol, and pentanol. These oxygen-rich compounds increase fuel atomization, decrease viscosity and density, increase the efficiency of combustion, and contribute to the reduction of pollutants like NOx, CO, and HC [5][4][1].

Higher alcohols like butanol and pentanol are getting interest because of their higher cetane number, greater miscibility with biodiesel, and decreased volatility compared to lower alcohols like ethanol and methanol [7], [8]. Alcohol additives have improved brake thermal efficiency (BTE), decreased brake specific fuel consumption (BSFC), and better emission profiles, even at low concentrations (typically 5–10% by volume) [2][5][6].

Studies have examined the cyclic variation in combustion utilizingtechniquesincluding the coefficient of variation (COV) and wavelet spectral analysis, for better emission and performance. According tothesestudies, alcohol additives can increase combustion variability due to their volatility and ignition characteristics, but their effect can beminimized and engine stability can be improved by optimized blending [3].

This study aims to investigate biodiesel and its production method, properties, types of additives, properties of additives, and effects of additives on biodiesel

II. Alcohol additives with biodiesel

2.1. Produce Biodiesel

Transesterification(Base-Catalysed Transesterification)

This is the most commonly used method[1-8]. In this method, Triglycerides (from vegetable oil or animal fats) and a short-chain alcohol (usually methanol or ethanol)are reacted in the presence of a base catalyst such as sodium hydroxide (NaOH) or potassium hydroxide (KOH).

To make biodiesel, Oils like palm or karanja are heated(up to 105°C) to remove water. ThenNaOH or KOH is dissolved in methanol to produce sodiummethoxide.The oil is mixed with sodium methoxide and heated (60–65°C) under stirring for1 hour.After settling, two layers form — biodiesel (methylesters) and glycerol.Then biodiesel is washed (with water or phosphoric acid) to remove impurities, then dried [1][4][8].

To create stable fuel blends, homogenization techniques are usedpost-transesterification, whenwe especiallyuse alcohol additives like ethanol or butanol [4][8]. For that, Magnetic or mechanical stirring is used at high RPM (e.g., 4000 rpm) to mix alcohols with biodiesel–diesel blends, to ensure miscibility and prevent phase separation [4].

2.2. Properties of Biodiesel

Biodiesel exhibits several unique physical and chemical characteristics that influence engine performance Compare to diesel.

- **Higher Viscosity**: the long-chain fatty acid estersin Biodiesel cause it to have significantly higher kinematic viscosity. since this increases lubrication, it can slow down atomization, especially in colder climates [1][4].
- **Higher Density**: The density of biodiesel is 0.86–0.89 kg/m³, which is higher than diesel's ~0.83–0.84 kg/m³. This can help to higher mass flow and change injection characteristics [4][5].
- **Lower Calorific Value**: Compared to diesel, biodiesel has about 10–12% less energy per unit volume, which results in a little lower power output and higher brake specific fuel consumption(BSFC) [2][4][5].
- **Higher Cetane Number**: Biodieselsusually have a cetane number between 75–98, higher than that of diesel (47–55) which helps better ignition quality and smoother combustion [4], [6].
- **Higher Flash Point**: Biodiesel is safer to store and move than diesel (~70°C) because its flash point is above 130°C and often up to 180°C[4].
- **Acid Value**: Biodiesel may have slightly higher acid value than diesel, which may affect long-term engine durability if not properly controlled.Acid value means the presence of free fatty acids. [4].

2.3. Types of Alcohol Additives

2.3.1 Ethanol (C_2H_5OH)

- Ethanol is the most common alcohol additive in biodiesel–diesel blends.
- It was usually added at 5% and 10% volume (B20E5, B20E10) to increase the ratio of fuel atomization and emissions [1][4][7][8].
- it has (34–35%) oxygen content improves combustion efficiency therefore reduces CO and HC emission ([2][4][5]).
- Its miscibility with diesel is poor, needs emulsifiers to form stable blends [2], [7].
- Bowed by its low cetane number and low flash point (16 degrees Celsius), ethanol may adversely affect the ignition delay and cyclic variation of the flame when not properly controlled [4][7][8].
- Ethanol mixed fuels, in some tests, showed higher HC emissions attributed to evaporation during expansion stroke [2].

2.3.2 Methanol (CH_3OH)

- It was used both as an additive and as a reactant in the transesterification process to produce biodiesel [1][3][4].
- When it is added to blends (e.g., B20M5, B20M10), methanol helps to reduce viscosity and flash point, improving cold-start performance [1][8].
- It has an extremely low cetane number (~3) and low flash point, which can result in delays in ignition and possible combustion instability at higher concentrations [8].
- Methanolhelps to oxygen enrichment, supporting more complete combustion and reducing certain emissions like CO and PM,like ethanol [4][5].

- If not properly stabilized,the poor miscibility of Methanolwith diesel canresultin phase separation [7].

2.3.3 n-Butanol (C_4H_9OH)

- n-Butanol is described as a superior alcohol additive compared to methanol and ethanol by its higher cetane number, more miscibility, and higher energy content ([2] [4][7]).
- Also, combinations such as D80P15B5 (80% diesel, 15% biodiesel, 5% butanol) showed lower BSFC and higher BTE than ethanol blends [2].
- Contribution of n-Butanol to reduction in NOx emissions due to higher heat of vaporization and lower in-cylinder temperature [4][7].
- Compared with ethanol, butanol-blended fuels showed lower hydrocarbon emissions and less cyclic variation in combustion [4][7][8].
- it was also noted that because butanol's fuel properties (viscosity, density) are closer to those of diesel, it is likely to be considered in high-blend biodiesel applications [5][8].

2.3.4 n-Pentanol ($C_5H_{11}OH$)

- n-Pentanol is another higher alcohol tested as an additive in biodiesel blends (e. g. D70P20Pe10).
- It has higher cetane number and energy content than ethanol and butanol and thus results in better ignition and power output [4][5].
- As reported by Mujtaba et al. [4], blends with n-pentanol showed the lowest BSFC and the highest BTE among all tested alcohols at high engine speeds.
- Although it reported good performance NOx emission was slightly higher than ethanol or butanol (probably due to higher combustion temperature [4][5]).
- It also showed excellent miscibility with diesel and biodiesel, potentially as a viable long-chain alcohol for fuel modification [5].

2.3.5 Diethyl Ether (DEE)

- n-Pentanol is another higher alcohol tested as an additive in biodiesel blends (e. g. D70P20Pe10).
- It is a higher cetane number and energy content than ethanol and butanol and thus results in better ignition and power output [4][5].
- As reported by Mujtaba et al. [4], blends with n-pentanol showed the lowest BSFC and the highest BTE among all tested alcohols at high engine speeds.
- Although it reported good performance NOx emission was slightly higher than ethanol or butanol (probably due to higher combustion temperature [4][5]).
- It also showed excellent miscibility with diesel and biodiesel, potentially as a viable long-chain alcohol for fuel modification [5].

2.3.6 Hexanol ($C_6H_{14}O$)

- Hexanol, a higher chain alcohol, was assessed as an oxygenated additive in diesel–biodiesel blends.
- It was used in a 10% blend in the form D70P20H10 (80% diesel, 20% palm biodiesel, 10% hexanol).
- Of the tested alcohols (ethanol, propanol, butanol, pentanol, hexanol) hexanol produced the lowest HC (hydrocarbon) emissions at higher engine speeds..
- Hexanol-blended fuels, on the other hand,
- reported higher NOx emissions probably due

- to higher in-cylinder temperatures (due to lower volatility and delayed evaporation rates) as compared to lighter alcohols.
- Hexanol blends also experienced lower CO emissions than diesel, owing to the content of oxygen, the study added.
- Although it was not most effective in reducing BSFC or encouraging BTE it played a positive role overall emission performance (particularly in terms of unburned hydrocarbons)
- DEE While not as commonly used as ethanol or butanol, dee found a proven performance-enhancing additive in biodiesel blend[4].

2.4. Properties of Alcohol Additives

The physical and combustion properties of alcohol additives significantly influence biodiesel fuel behavior. These include:

- **Oxygen Content:** Alcohols like ethanol (34%) and methanol (35%) supply more oxygen to the combustion process, improving the oxidation of hydrocarbons and reducing emissions [1][5].
- **Latent Heat of Vaporization:** Alcohols absorb more heat during vaporization, which lowers the in-cylinder temperature and helps reduce NOx emissions but may delay ignition and increase cyclic variation [5][8].
- C**etane Number:** methanol and ethanol have a lower CetaneNumber (3–8), butanol and pentanol have moderate (~25–35), and very high in DEE (>125). A higher cetane number promotes better ignition quality [4][5][7].
- **Miscibility:** Ethanol and methanol have poor solubility in diesel without emulsifiers, which can resultin phase separation, but Butanol, pentanol, an DEE show excellent solubility across fuel ranges [2][5][7].
- **Flash point:** Alcohols have a lower flash point, which may influence safety during handling and may affect ignition delay if not properly controlled [7]

2.5. Effects of Alcohol Additives on Biodiesel Fuel Characteristics

When alcohols are added to biodiesel–diesel blends, they enhance fuel properties and combustion outcomes:

- **Reduction in Viscosity and Density:** Alcohols help to reduce the viscosity and density of biodiesel blends and improve the atomisation and vapour characteristics of the fuel [1][4].
- **Lower Flash Point:** The flash point decreases with alcohols, which improves ignition at lower temperatures but requires careful safety management [4][2].
- **Improved Combustion Efficiency:** Oxygenated alcohols promote more complete combustion, improving BTE and reducing unburned hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM) emissions [5][6][7].
- **Reduced NOx Emissions:** The addition of alcohol generally reduces CO and PM emissions by increasing the oxygen content, although NOx emissions vary according to the type of alcohol and the proportion of alcohol in the blend [5][7].
- **Potential Increase in Combustion Variability:**Alcohols,especially ethanol and methanol, may increase cycle-to-cycle variations (COV), which can affect stability and smoothness of engine operation, due to their volatility and ignition characteristics [8].

- **Slight Increase in BSFC:** Despite increased combustion, the lower calorific value of alcohols (especially ethanol and methanol) may result in a small increase in fuel consumption unless balanced by greater thermal efficiency [2][5].

III. CONCLUSION

This review looks at issues related to biodiesel use in diesel engines and also looks at the large part that alcohol additives play in biodiesel performance. While biodiesel does have very useful environmental benefits that include lower greenhouse gas output and being a renewable source, it also has issues such as high viscosity, density, low energy content and poor cold weather performance that limit its use in present day engines. Also we see that higher alcohols like butanol and pentanol included in the biodiesel mix do very well in solving these problems by which they reduce viscosity, improve spray pattern, increase burn efficiency, and reduce soot and CO emissions. But what also is very important is that the type and ratio of alcohol used is a key issue too much alcohol can actually reduce the flash point of the fuel, damage the quality of the ignition and also cause cyclic changes in the engine which affects performance.

The research shows that adding 5-10% alcohol at a reasonable concentration improves the performance of the biodiesel/diesel mixture, without adversely affecting engine performance or safety.We also put forth that it is of great importance to choose the right alcohol types, do the blend just right, and at the same time to study how they in turn play a role in biodiesel properties' behaviour, which is a key to the sustainable and efficient use of biodiesel as a diesel alternative. Also to be looked at going forward is the issue of what these alcohol biodiesel blends do to engine durability in the long term and the development of reliable standards which in turn will help in the broad-scale commercial adoption of biodiesel

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Review of Biofuel from Waste Cooking Oil for Compression Ignition Engines

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ABSTRACT

Biodiesel derived from waste cooking oil (WCO) appears to be a promising renewable fuel for compression ignition (CI) engines, potentially reducing environmental impact while utilizing waste resources. This review synthesizes current research on WCO biodiesel, focusing on production methods, properties, engine performance, emissions, and comparisons with other biodiesels like soybean and rapeseed. Transesterification, often requiring pre-treatment for high free fatty acid (FFA) content, is the primary production method. WCO biodiesel exhibits higher viscosity and density but comparable cetane numbers to diesel. Engine performance studies suggest slightly lower brake thermal efficiency (BTE) and higher specific fuel consumption (SFC), while emissions data indicate reductions in carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM), though nitrogen oxides (NOx) may increase. Compared to other biodiesels, WCO biodiesel offers sustainability advantages but faces challenges like feedstock variability and production costs. This paper highlights WCO biodiesel's potential and identifies future research directions to optimize its use in CI engines.

Keywords: Biodiesel, Waste Cooking Oil, Transesterification, Compression Ignition Engine, Emissions

I. INTRODUCTION

The global energy landscape is undergoing a significant transformation driven by rising demand, depleting fossil fuel reserves, and pressing environmental concerns. In 2024, global energy demand grew by 2.2%, surpassing the average annual growth of 1.3% observed between 2013 and 2023, largely due to economic development and extreme weather conditions [1]. This surge underscores the urgent need for sustainable energy alternatives to mitigate climate change and reduce reliance on non-renewable resources. Biodiesel, a renewable fuel derived from biological sources, has emerged as a viable substitute for petroleum diesel in compression ignition (CI) engines, offering a pathway to lower greenhouse gas emissions and enhanced energy security.

Biodiesel is produced through transesterification, a process that converts triglycerides into fatty acid methyl esters (FAME) and glycerol, making it compatible with existing diesel engines. Unlike fossil fuels, biodiesel is biodegradable, non-toxic, and can be sourced from various feedstocks, including vegetable oils, animal fats, and waste cooking oil (WCO). Among these, WCO stands out as a cost-effective and environmentally beneficial feedstock due to its abundance and the potential to address waste management challenges. In Malaysia, for instance, approximately 540,000 tonnes of WCO are discarded annually, highlighting its availability as a resource [2].

The improper disposal of WCO poses significant environmental risks. When poured down drains, WCO can clog sewage systems, leading to overflows that contaminate rivers and oceans. It forms thick layers on water surfaces, suffocating aquatic life and disrupting ecosystems [3]. Additionally, WCO in landfills contributes to methane emissions, a potent greenhouse gas. Converting WCO into biodiesel mitigates these issues, transforming a waste product into a valuable energy source while reducing environmental pollution.

Economically, WCO biodiesel offers substantial advantages. The cost of WCO is significantly lower than that of virgin oils, which can account for up to 75% of biodiesel production costs [4]. By utilizing WCO, producers can reduce raw material expenses, making biodiesel more competitive with petroleum diesel. Furthermore, WCO collection and processing can create jobs and stimulate local economies, particularly in regions with high WCO generation.

Compression ignition (CI) engines, commonly used in transportation, agriculture, and industry, are ideal candidates for biodiesel due to their efficiency and durability. These engines operate by compressing air to ignite the fuel, and biodiesel's similar properties to diesel allow its use with minimal engine modifications. WCO biodiesel, in particular, offers improved lubricity and a higher cetane number, enhancing engine performance and longevity [5].

The environmental benefits of WCO biodiesel in CI engines are notable. Research suggests that it reduces emissions of carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM) compared to diesel, although nitrogen oxides (NOx) emissions may increase due to higher combustion temperatures [6].

These characteristics position WCO biodiesel as a cleaner alternative, contributing to improved air quality and reduced environmental impact.

Despite its potential, WCO biodiesel faces challenges that hinder widespread adoption. Variability in WCO quality, due to differences in source and degradation, can affect biodiesel consistency. High FFA content requires additional processing, increasing production costs. Logistical issues, such as establishing efficient WCO collection systems, also pose barriers, particularly in regions with limited infrastructure [7].

The global biodiesel market is expanding, with consumption reaching 65.86 million metric tons in 2023 and projected to grow further. WCO biodiesel's role in this market is significant, given its sustainability and economic advantages. However, comparisons with other biodiesels, such as those from soybean or rapeseed, are essential to understand its relative performance and viability.

This review aims to provide a comprehensive analysis of WCO biodiesel for CI engines, covering production methods, properties, engine performance, emissions, and comparisons with other biodiesels. It also explores environmental and economic benefits, challenges, and future prospects, synthesizing data from recent studies to inform researchers, policymakers, and industry stakeholders.

The paper is structured as follows: Section II details production methods, Section III compares WCO biodiesel properties, Section IV evaluates engine performance, Section V analyzes emissions, Section VI compares WCO biodiesel with other biodiesels, Section VII discusses environmental and economic benefits, Section VIII addresses challenges and future prospects, and Section IX concludes with key findings and recommendations.

II. PRODUCTION METHODS OF BIODIESEL FROM WASTE COOKING OIL

Producing biodiesel from WCO involves converting triglycerides into FAME through transesterification, a process that requires careful consideration of WCO's high FFA content and variability. This section elaborates on the transesterification process, catalysts, reaction conditions, and emerging techniques, drawing on recent studies to provide a comprehensive overview.

A. Transesterification Process

Transesterification is the most widely used method for biodiesel production due to its cost-effectiveness and mild reaction conditions. In this process, WCO reacts with an alcohol, typically methanol, in the presence of a catalyst to produce FAME and glycerol. However, WCO often contains high levels of FFAs (>1%), which can react with base catalysts to form soap, reducing yield and complicating separation. To address this, a two-step process is commonly employed: acid-catalyzed esterification to reduce FFAs, followed by base-catalyzed transesterification. A study achieved a 98.8% conversion rate using a two-stage process with radio frequency heating, demonstrating improved efficiency [8].

The esterification step uses an acid catalyst, such as sulfuric acid (H_2SO_4), to convert FFAs into esters, lowering the FFA content to below 1%. The subsequent transesterification step employs a base catalyst to complete the conversion to biodiesel. This two-step approach is particularly effective for WCO with FFA levels up to 68.2 mg KOH/g, achieving high yields with minimal byproducts [9].

B. Catalysts

Catalysts are critical to transesterification efficiency. Homogeneous base catalysts, such as sodium hydroxide (NaOH) and potassium hydroxide (KOH), are widely used for their fast reaction rates and low cost. However, they are less effective with high-FFA WCO due to soap formation. Heterogeneous catalysts, like calcium oxide (CaO), offer advantages such as reusability and easier separation. A nano-CaO catalyst, calcinated at 500°C, achieved a 96% biodiesel yield at 50°C with a 1:8 oil-to-methanol ratio, highlighting the potential of nanotechnology [10].

Bifunctional catalysts, capable of simultaneous esterification and transesterification, are emerging as a solution for high-FFA WCO. These catalysts reduce processing steps and costs, with studies reporting yields above 90% under optimized conditions [7]. Enzymatic catalysts, such as lipases, are environmentally friendly but currently less viable due to high costs and slower reaction rates. Supercritical transesterification, which operates without catalysts under high temperature and pressure, shows promise but requires significant energy input, limiting its commercial adoption [2].

C. Reaction Conditions

Optimal transesterification conditions balance yield, cost, and energy efficiency. Typical parameters include a methanol-to-oil molar ratio of 6:1 to 9:1, catalyst concentration of 0.5–2.0 wt%, reaction temperature of

50–65°C, and reaction time of 1–2 hours. Excess methanol drives the reaction forward, but higher ratios increase recovery costs. For high-FFA WCO, esterification uses 3.0% H_2SO_4 with a 20:1–40:1 methanol-to-oil ratio at 60°C for 1–2 hours, reducing FFA to levels suitable for transesterification [9].
Response surface methodology is often used to optimize these parameters, accounting for WCO's variability. A study reported that a 1:8 methanol-to-oil ratio, 1% CaO catalyst, and 90-minute reaction time at 50°C maximized yield at 96% [10]. These conditions are tailored to WCO's composition, which varies based on oil type and cooking conditions, ensuring consistent biodiesel quality.

D. Emerging Techniques

Recent advancements include microwave-assisted transesterification, which reduces reaction time and energy consumption, and ultrasound-assisted methods, which enhance mixing and yield. A study using microwave heating achieved a 95% yield in 30 minutes, compared to 1–2 hours for conventional methods [8]. These techniques, while promising, require further development to scale up cost-effectively.

TABLE I

Summarizes key studies on WCO biodiesel production methods, highlighting catalysts, conditions, and yields.

Study	Catalyst	Methanol:Oil Ratio	Temperature (°C)	Time (min)	Yield (%)	Reference
Nano-CaO	CaO (nano)	1:8	50	90	96	[10]
Two-step	H_2SO_4, NaOH	20:1 (ester), 6:1	60, 65	120, 60	98.8	[8]
Microwave	KOH	1:6	60	30	95	[8]

III. PROPERTIES OF WASTE COOKING OIL BIODIESEL

WCO biodiesel's properties, influenced by its fatty acid composition, determine its suitability for CI engines. Table II compares key properties with diesel and other biodiesels.

TABLE III

Properties of Biodiesels from Different Feedstocks [11]

Feedstock	Viscosity (mm^2/s, 40°C)	Density (g/cm^3, 21°C)	Cetane Number	Flash Point (°C)	Cloud Point (°C)	Pour Point (°C)
Diesel	2.0–4.5	0.820–0.860	51.0	55	-18	-25
WCO Methyl Ester	4.5–5.5	0.880–0.900	50–60	>120	5–15	0–10
Soybean Methyl Ester	4.08	0.884	50.9	131	-0.5	-4
Rapeseed Methyl Ester	4.83	0.882	52.9	155	-4	-10.8
Sunflower Methyl Ester	4.60	0.880	49.0	183	1	-7
Tallow Methyl Ester	5.00	0.877	58.8	150	12	9

WCO biodiesel's higher viscosity (4.5–5.5 mm²/s) and density (0.880–0.900 g/cm³) compared to diesel (2.0–4.5 mm²/s, 0.820–0.860 g/cm³) can affect fuel atomization and injection. Its cetane number (50–60) is comparable or higher, ensuring good ignition quality. The flash point (>120°C) enhances safety, but higher cloud (5–15°C) and pour points (0–10°C) indicate potential cold weather issues due to high saturated fatty acid content (40–43% palmitic, 14–18% oleic) [11].

Compared to soybean biodiesel, WCO biodiesel has higher viscosity and cloud points but similar cetane numbers. Rapeseed biodiesel offers better cold flow properties but lower cetane numbers, while tallow biodiesel has higher cetane numbers but poorer cold flow performance [11].

IV. PERFORMANCE OF CI ENGINES WITH WCO BIODIESEL

WCO biodiesel's performance in CI engines is evaluated through brake thermal efficiency (BTE), specific fuel consumption (SFC), power, and torque, with studies focusing on various blends (B10, B20, B50, B100).

A. Brake Thermal Efficiency (BTE)

BTE is slightly lower for WCO biodiesel due to its lower calorific value (37–40 MJ/kg vs. 42–45 MJ/kg for diesel). A study reported 26% BTE for B100 compared to 30% for diesel at full load, attributed to higher viscosity and lower energy content [6]. B20 blends show closer performance, with BTE at 29.5% [12].

B. Specific Fuel Consumption (SFC)

SFC is higher for WCO biodiesel due to its lower energy content. For B100, SFC was 0.351 kg/kWh compared to 0.275 kg/kWh for diesel [13]. B20 blends have SFC closer to diesel, at 0.290 kg/kWh [12].

C. Power and Torque

Power and torque are comparable but slightly reduced for higher biodiesel blends. B100 showed a torque drop of 1.9–5.4 Nm across speeds, while B20 maintained performance close to diesel [12].

TABLE IIIII

Performance Characteristics of CI Engines with WCO Biodiesel Blends [12]

Fuel	BTE (%)	SFC (kg/kWh)	Torque (Nm)
Diesel	30	0.275	100
B20	29.5	0.290	98
B50	28	0.310	95
B100	26	0.351	90

V. EMISSIONS FROM CI ENGINES WITH WCO BIODIESEL

WCO biodiesel impacts emissions differently compared to diesel, with reductions in some pollutants and increases in others.

A. Carbon Monoxide (CO)

CO emissions decrease due to higher oxygen content, with reductions up to 59% for B20 and 31% for B100 [6].

B. Unburned Hydrocarbons (HC)

HC emissions drop by up to 57% across blends, reflecting improved combustion efficiency [6].

C. Particulate Matter (PM)

PM and smoke opacity decrease, particularly at high loads, due to lower carbon-to-hydrogen ratios [14].

D. Nitrogen Oxides (NOx)

NOx emissions increase, with an 18.33% rise for B100 at full load, linked to higher combustion temperatures [6].

TABLE IVV

Emissions from CI Engines with WCO Biodiesel Blends [6]

Fuel	CO (% Reduction)	HC (% Reduction)	NOx (% Change)	Smoke Opacity
Diesel	0	0	0	Baseline
B20	59	57	+10	Lower at high load
B40	38	57	+12	Lower at high load
B80	35	57	+15	Lower at high load
B100	31	57	+18.33	Lower at high load

VI. COMPARISON WITH OTHER BIODIESELS

WCO biodiesel's performance and emissions are compared with other biodiesels, such as soybean, rapeseed, and tallow, to assess its relative advantages.

A. Properties Comparison

WCO biodiesel has higher viscosity and cloud points than soybean and rapeseed biodiesels, which can affect cold weather performance. However, its cetane number is comparable, ensuring similar ignition quality. Tallow biodiesel has a higher cetane number but poorer cold flow properties [11].

B. Performance Comparison

Soybean biodiesel slightly outperforms WCO biodiesel in BTE and torque due to lower viscosity. A study reported B10 soybean biodiesel achieving 99.56% of diesel power compared to 99.35% for WCO B10 [11].

C. Emissions Comparison

WCO biodiesel reduces CO more effectively than soybean biodiesel (63.97% vs. 75.17% reduction for B10 blends) but increases NOx slightly more (124.82% vs. 119.60%) [11].

TABLE V

Performance and Emissions of B10 Biodiesel Blends [11]

Parameter	Diesel	Soybean B10	WCO B10
Power (% of diesel)	100	99.56	99.35
Torque (% of diesel)	100	99.09	98.64
BSFC (kg/kWh)	0.28	0.306	0.312
CO (% of diesel)	100	75.17	63.97

NOx (% of diesel)	100	119.60	124.82

VII. ENVIRONMENTAL AND ECONOMIC BENEFITS

WCO biodiesel reduces greenhouse gas emissions and waste disposal issues, preventing water and soil contamination. Economically, it lowers production costs by 70–80% compared to virgin oils, creating jobs and supporting energy independence [7].

VIII. CHALLENGES AND FUTURE PROSPECTS

Challenges include WCO quality variability, high production costs for high-FFA oils, and engine compatibility with high blends. Future research should focus on advanced catalysts, engine optimization, and policy incentives to enhance adoption [7].

IX. CONCLUSION

WCO biodiesel is a sustainable and economically viable fuel for CI engines, offering significant environmental benefits through reduced emissions and waste management. Its production via transesterification is well-established, though high FFA content requires tailored processes. Engine performance is slightly lower than diesel, with higher SFC and lower BTE, but emissions of CO, HC, and PM are reduced, despite increased NOx. Compared to soybean and rapeseed biodiesels, WCO biodiesel excels in sustainability but faces challenges in cold weather performance and NOx emissions. Addressing technical and logistical barriers through advanced catalysts, optimized engine designs, and robust collection systems will enhance its adoption. Policy support, such as subsidies and mandates, can further promote WCO biodiesel, positioning it as a cornerstone of the circular economy and a key contributor to global energy sustainability.

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Production of Biofuels from Waste Food and Vegetables for Engine Applications: A Review

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ABSTRACT

This review examines the production and application of biofuels, specifically bioethanol, biodiesel, and biogas, derived from waste food and vegetables for use in internal combustion engines. It synthesizes current technologies, including enzymatic hydrolysis, fermentation, transesterification, and anaerobic digestion, and evaluates their yields, efficiencies, and environmental impacts. Research suggests that bioethanol yields from household food waste can reach approximately 108 g/kg dry matter, while biodiesel from used cooking oil achieves over 90% yield. These biofuels offer significant greenhouse gas savings, with biodiesel from waste oil potentially reducing emissions by over 80% compared to fossil diesel. Engine performance studies indicate trade-offs, such as increased fuel consumption but reduced carbon monoxide emissions. Challenges include feedstock variability, processing costs, and scalability, with advancements in microbial strains and catalysts addressing these issues. The review highlights the potential of waste-derived biofuels to support sustainable energy and waste management, providing insights for researchers and policymakers.

Keywords: Biofuel, food waste, vegetable waste, bioethanol, biodiesel, biogas, engine performance, sustainability, transesterification, fermentation

I. INTRODUCTION

The global energy landscape faces unprecedented challenges due to the depletion of fossil fuel reserves and escalating environmental concerns, particularly greenhouse gas (GHG) emissions contributing to climate change. With the International Energy Agency reporting a steady rise in global energy demand, the need for sustainable and renewable energy sources has never been more critical. Biofuels, derived from biomass, have emerged as a viable alternative, offering the potential to reduce carbon footprints and enhance energy security [1].

Food waste represents a significant global issue, with the Food and Agriculture Organization (FAO) estimating that approximately 1.3 billion tonnes of food are wasted annually, equivalent to one-third of global food production. This waste not only squanders resources but also contributes to environmental degradation through methane emissions from landfills, which account for about 8% of global GHG emissions. In developed nations, consumer-level waste dominates, with per capita figures reaching 95-115 kg/year in Europe and North America, compared to 6-11 kg/year in sub-Saharan Africa and South/Southeast Asia.

The valorization of food waste into biofuels offers a dual solution to energy scarcity and waste management. Waste food and vegetables, rich in carbohydrates, lipids, and organic matter, serve as ideal feedstocks for producing bioethanol, biodiesel, and biogas. These biofuels can power internal combustion engines, either as standalone fuels or blends, reducing reliance on fossil fuels and mitigating environmental impacts [2].

Bioethanol, produced through fermentation of carbohydrate-rich waste like fruit peels and bread, is commonly blended with gasoline for spark-ignition engines. Biodiesel, derived from lipid-rich waste such as used cooking oil via transesterification, is used in diesel engines. Biogas, primarily methane from anaerobic digestion, can fuel natural gas engines or be upgraded to biomethane for vehicle use. These processes leverage waste materials that would otherwise be discarded, avoiding competition with food production, a key criticism of first-generation biofuels from crops like corn and soybeans.

The environmental benefits of waste-derived biofuels are substantial. Life cycle assessments (LCAs) indicate that biodiesel from used cooking oil can achieve GHG savings of over 80% compared to fossil diesel, while bioethanol from food waste significantly reduces landfill methane emissions [3].

Economically, these biofuels can be cost-competitive due to low or negative feedstock costs, though processing and logistics remain challenges.

Globally, biofuel production is expanding, with bioethanol reaching 110 billion liters and biodiesel 47 billion liters in 2019. The United States, Brazil, and the European Union lead production, but waste-derived biofuels are gaining traction, driven by policies like the Renewable Fuel Standard and the EU's Renewable Energy Directive. These policies promote blending mandates and incentives, fostering market growth.

Successful implementations highlight the potential of waste-derived biofuels. In Sweden, food waste is converted into biogas to power public transportation, while in the United States, companies like Renewable Energy Group produce biodiesel from waste oils. These case studies demonstrate practical applications and scalability potential.

Despite these advancements, challenges persist, including feedstock variability, high processing costs, and logistical complexities. Research is ongoing to optimize conversion technologies and improve economic viability, making waste-derived biofuels a cornerstone of sustainable energy strategies.

This review aims to synthesize current knowledge on biofuel production from waste food and vegetables, focusing on their suitability for engine applications. It covers production technologies, engine performance, environmental and economic impacts, and challenges, providing a comprehensive resource for researchers, policymakers, and students.

The objectives are to evaluate the feasibility of these biofuels, highlight technological advancements, and identify future research directions to enhance their adoption in a low-carbon economy. By addressing these aspects, this paper contributes to the discourse on sustainable energy and waste management.

II. METHODS

A systematic and comprehensive literature review was conducted to gather and synthesize information on the production and application of biofuels derived from waste food and vegetables for engine use. The methodology was designed to ensure a robust and representative selection of studies, focusing on peer-reviewed research to maintain academic rigor and relevance. The review process involved multiple stages, including literature search, study selection, data extraction, and synthesis, with an emphasis on recent advancements to reflect the current state of the field.

A. Literature Search Strategy

The literature search was performed using academic databases such as PubMed, ScienceDirect, Google Scholar, and Wiley Online Library, which are recognized for hosting high-quality scientific publications. Keywords and phrases used included “biofuel from food waste,” “bioethanol from vegetable waste,” “biodiesel from waste cooking oil,” “biogas from food waste,” “engine performance with biofuels,” “emission characteristics of biofuels,” and “life cycle assessment of biofuels.” Boolean operators (AND, OR) were employed to refine searches, combining terms to capture relevant studies. For example, searches like “bioethanol AND food waste AND engine” were used to target specific applications.

To ensure comprehensive coverage, additional sources such as reports from reputable organizations (e.g., FAO, International Energy Agency) and conference proceedings were included. The search was restricted to publications in English to facilitate analysis, with a focus on articles published between 2010 and 2024 to capture recent technological advancements and policy developments. This timeframe was chosen to reflect the rapid evolution of biofuel technologies and their increasing relevance in sustainable energy systems.

B. Study Selection Criteria

Studies were selected based on predefined inclusion and exclusion criteria to ensure relevance and quality. Inclusion criteria encompassed:

- Peer-reviewed articles, review papers, or technical reports addressing biofuel production from waste food and vegetables.
- Studies focusing on bioethanol, biodiesel, or biogas, with an emphasis on their application in internal combustion engines.
- Research providing quantitative data on yields, engine performance metrics (e.g., brake thermal efficiency, specific fuel consumption), emission characteristics (e.g., CO, NOx, particulate matter), or environmental and economic impacts.
- Publications detailing production technologies, such as fermentation, transesterification, or anaerobic digestion, and their optimization.

  Exclusion criteria included:
- Studies focusing solely on first-generation biofuels from food crops, as these compete with food production.
- Articles lacking empirical data or relying on speculative analyses.
- Non-English publications or those outside the 2010-2024 timeframe, unless seminal works provided critical context.

C. Data Extraction and Synthesis

Selected studies were analyzed to extract key data, including:

- Feedstock types and their chemical composition (e.g., carbohydrate, lipid content).
- Biofuel production processes and yields (e.g., g/kg for bioethanol, % yield for biodiesel).
- Engine performance metrics, such as brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), power output, and torque.
- Emission profiles, including carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter (PM).
- Environmental impacts, such as GHG savings from life cycle assessments.
- Economic analyses, including production costs and market potential.

Data were organized into thematic categories corresponding to the review's structure: types of biofuels, production technologies, engine performance, emissions, environmental and economic impacts, and challenges. Quantitative data were tabulated for comparison, while qualitative insights were synthesized to provide a narrative overview. Discrepancies in reported yields or performance metrics were noted, and potential reasons (e.g., feedstock variability, experimental conditions) were explored.

D. Quality Assessment

To ensure data accuracy, studies were evaluated for methodological rigor, including sample size, experimental design, and statistical analysis. Peer-reviewed articles from high-impact journals were prioritized, and cross-referencing was used to verify consistency across sources. Where possible, data were compared with industry reports or standards (e.g., ASTM D6751 for biodiesel) to confirm reliability. Limitations in the literature, such as small-scale experiments or regional biases, were acknowledged to provide a balanced perspective.

E. Analytical Approach

The review adopted a mixed-methods approach, combining quantitative data analysis (e.g., yield comparisons, emission reductions) with qualitative synthesis of technological trends and policy implications. Tables were used to present comparative data, such as biofuel yields and engine performance metrics, while narrative discussions explored complex issues like scalability and environmental trade-offs. The synthesis aimed to address the review's objectives: evaluating feasibility, highlighting advancements, and identifying research gaps.

This methodology ensured a thorough and systematic exploration of the topic, providing a robust foundation for the review's findings. The process was iterative, with additional searches conducted to address gaps identified during analysis, ensuring comprehensive coverage of the subject matter.

III. RESULTS AND DISCUSSION

A. Types of Biofuels from Waste Food and Vegetables

1. Bioethanol

Bioethanol is produced from carbohydrate-rich food waste, such as fruit peels, vegetable residues, and bakery waste, through fermentation. The process involves pretreatment to break down complex carbohydrates, enzymatic hydrolysis to convert them into fermentable sugars, and fermentation using microorganisms like Saccharomyces cerevisiae. Studies report yields of 107.58 g/kg dry matter from household food waste at 45% solids content [4] and up to 144 g/L from mixed food waste [5].

2. Biodiesel

Biodiesel is derived from lipid-rich waste, primarily used cooking oil (UCO), through transesterification, producing fatty acid methyl esters (FAME). Yields are high, with studies reporting 91.45–96% under optimized conditions using catalysts like calcium oxide [6]. UCO, constituting ~10% of global biodiesel production, is abundant and cost-effective.

3. Biogas

Biogas, primarily methane, is produced via anaerobic digestion of organic-rich food waste. It can be upgraded to biomethane for use in natural gas engines. Yields vary, with fruit waste producing up to 89% biogas, upgradeable to 99% biomethane purity [7].

TABLE I

Biofuel Yields from Food Waste Feedstocks

Feedstock	Biofuel Type	Yield	Reference
Household food waste	Bioethanol	107.58 g/kg dry matter	[4]
Mixed food waste	Bioethanol	144 g/L	[5]
Used cooking oil	Biodiesel	91.45–96%	[6]
Fruit waste	Biogas	89% (biogas)	[7]

B. Production Technologies

1. Bioethanol Production

Bioethanol production involves pretreatment (physical, chemical, or enzymatic), hydrolysis, fermentation, and distillation. Advanced techniques like simultaneous saccharification and fermentation (SSF) improve yields, with SSF increasing ethanol yield by 77% at 20% solids loading [8]. Engineered strains like Zymomonas mobilis achieve high yields, producing 99.8 g/L from food waste hydrolysate [9].

2. Biodiesel Production

Transesterification is the primary method, using alkali, acid, or enzymatic catalysts. Nano-catalysts like CaO enhance yields, with optimal conditions yielding 96% biodiesel [6]. Enzymatic methods reduce environmental impact but are costlier.

3. Biogas Production

Anaerobic digestion involves hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Co-digestion with manure or sludge boosts methane yields, with studies reporting 200-300 m^3/ton from vegetable waste [10].

C. Engine Performance

1. Bioethanol in Spark-Ignition Engines

Bioethanol blends (e.g., E10, E20) increase octane ratings, improving efficiency but raising BSFC due to lower energy content. A study on waste bread bioethanol showed reduced combustion times and lower cylinder pressures [11].

2. Biodiesel in Compression-Ignition Engines

Biodiesel blends (e.g., B20) exhibit lower BTE (28.5% vs. 29.8% for diesel) and higher BSFC (270 g/kWh vs. 245 g/kWh) [12]. Improved lubricity extends engine life.

TABLE II

Engine Performance Metrics

Fuel Type	BTE (%)	BSFC (g/kWh)	Reference
Diesel	29.8	245	[12]
B20 (WCO)	28.5	270	[12]
E20 (Waste bread)	Not specified	Increased	[13]

D. Emission Characteristics

Biodiesel blends reduce CO (by 18.6% for B20), HC (by 26.7%), and smoke opacity (by 20.58%) but increase NOx [14]. Bioethanol blends lower CO and HC but may increase NOx and aldehydes.

E. Environmental and Economic Impacts

LCAs show biodiesel from UCO achieves over 80% GHG savings, while bioethanol reduces landfill methane emissions [13]. Economically, waste feedstocks lower costs, but processing and logistics are significant. Integrated biorefineries enhance profitability [10].

F. Challenges and Advancements

Challenges include feedstock variability, high moisture content, and collection costs. Advancements involve enzyme engineering, nano-catalysts, and policy incentives. Future research should focus on scalable technologies and standardized waste collection systems.

IV. CONCLUSION

The production of bioethanol, biodiesel, and biogas from waste food and vegetables represents a transformative approach to addressing global energy and environmental challenges. These biofuels leverage abundant waste resources to produce renewable fuels compatible with existing engine technologies, offering significant environmental benefits. Research indicates that bioethanol yields from household food waste can reach 108 g/kg dry matter, while biodiesel from used cooking oil achieves over 90% yield, with GHG savings exceeding 80% for biodiesel compared to fossil diesel. Engine performance studies reveal trade-offs, such as increased fuel consumption but reduced CO and HC emissions, highlighting the need for optimized blends and engine adjustments.

The environmental advantages are compelling, with waste-derived biofuels reducing landfill methane emissions and supporting a circular economy. Economically, these biofuels benefit from low-cost feedstocks, though processing and logistical challenges remain. Technological advancements, including enzyme engineering and nano-catalysts, are improving yields and cost-effectiveness, while policy incentives are driving adoption.

However, challenges persist, including feedstock variability, high moisture content, and the need for efficient collection systems. These hurdles underscore the importance of continued research into scalable technologies and standardized waste management practices. Integrated biorefineries, combining biofuel production with other value-added products, offer a promising path to enhance economic viability.

The potential of waste-derived biofuels extends beyond energy production, contributing to sustainable development goals by addressing waste management, energy security, and climate change. Successful implementations, such as Sweden's biogas-powered public transport and the United States' biodiesel production from waste oils, demonstrate practical feasibility and scalability.

Future research should prioritize optimizing conversion processes, developing robust microbial strains, and improving feedstock logistics. Policy frameworks should focus on incentivizing waste-to-energy initiatives and establishing global standards for biofuel quality and sustainability. By addressing these areas, waste-derived biofuels can play a pivotal role in transitioning to a low-carbon economy, offering a sustainable and innovative solution to pressing global challenges.

This review underscores the multifaceted benefits of biofuels from waste food and vegetables, providing a foundation for further exploration and implementation. As technological and policy landscapes evolve, these biofuels are poised to become integral to sustainable energy systems, benefiting both the environment and society.

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Review on a Solar Powered Vehicle

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ABSTRACT

Solar vehicles offer a sustainable alternative to conventional transportation by harnessing solar energy for propulsion, significantly reducing greenhouse gas emissions and fossil fuel dependency. This review paper provides an in-depth examination of the fundamental technologies, design methodologies, and operational principles behind solar powered electric vehicles (SPEVs). It explores key components such as photovoltaic (PV) panels, energy storage systems, power electronics, and electric drivetrains. The paper also reviews recent advancements in solar cell efficiency, lightweight materials, and vehicle energy management strategies. Various prototypes and real-world applications are analyzed to assess performance, efficiency, and viability. Challenges related to limited solar energy availability, high initial costs, and integration with existing infrastructure are critically discussed. The review concludes with future research directions aimed at enhancing the commercial potential and adoption of solar vehicles through innovations in materials, hybridization, and intelligent control systems.

Keywords: Solar Vehicle, Photovoltaic System, Electric Vehicle, Renewable Energy, Energy Storage, Vehicle Design

I. INTRODUCTION

A long time ago, people discovered fuels like petrol and diesel deep underground. These fuels became very popular because they could power cars, buses, trucks, and even airplanes. Life became faster and easier—but not without a cost. Every time a car engine burns fuel, it lets out smoke and gases into the air. [1] These gases, like carbon dioxide, slowly warm up the Earth, causing problems like rising temperatures, melting ice, and changing weather [1,2] The smoke also pollutes the air we breathe, making people sick, especially in big cities. Getting these fuels out of the ground means digging deep, sometimes harming forests, rivers, and animals. Sometimes, there are oil spills in oceans, which hurt sea life badly. And since these fuels are not endless, one day they will run out. On top of that, fuel prices keep changing, and they can get very expensive. Engines that run on fuel also make a lot of noise and need more repairs. [2] So while fuel helped us grow, it's now hurting our planet. That's why many people are looking for cleaner, safer ways to travel—like using energy from the sun.

As the world faces serious problems like pollution, climate change, and the depletion of fossil fuels, The need for clean and renewable energy sources has become more important than ever. One of the most promising solutions in the field of transportation is the solar- powered vehicle. These vehicles use energy from the sun to move, making them eco-friendly and a great alternative to traditional fuel-based vehicles. [6,7] Usually, photovoltaic (PV) cells contained in solar panels converts the sun's energy directly into electric energy. The term ―Solar Vehicle‖ usually implies that solar energy is used to power all or part of a vehicle's propulsion [7,8] Solar power may be also used to provide power for communications or controls or other auxiliary function. Solar vehicles are not sold as practical day to-day transportation devices at present, but are primarily demonstration vehicles and engineering exercises, often sponsored by government agencies.

One of the most compelling reasons for transitioning to solar cars is their minimal environmental impact. Unlike IC engine vehicles that emit large amounts of carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulate matter, solar cars produce zero tailpipe emissions. These pollutants from IC vehicles are among the primary causes of air pollution in cities, leading to respiratory problems, heart disease, and even premature deaths [8,9,10]. Moreover, CO_2 emissions are a major contributor to the greenhouse effect and global warming.

To protect our planet and our health, we need better fuels to replace petrol and diesel. A good alternative fuel should be clean and not release harmful gases into the air. [4] It must be safe for people, animals, and the environment. [3,4] The fuel should come from renewable sources, so it won't run out. It needs to help fight climate change by reducing greenhouse gases. It should also be easy to use in cars, buses, and trucks. The cost of using it should be low in the long run.

By reading previous papers I know that it will have some drawbacks. Some fuels like biofuel require large amounts of land, water, and crops, which can affect food supply. Solar and wind energy depend on weather, so they don't always produce power when needed. Electric vehicles need batteries that use rare metals, which can be hard to mine and recycle. [5] Building new systems for alternative fuels can be expensive and take time. Charging stations for electric vehicles are still not available everywhere. Hydrogen fuel is clean but storing and transporting it safely is difficult. Some alternative fuels don't give as much energy as petrol or diesel. Also, changing to new fuel types means changing technology, which can be costly. In some places, people may not trust or understand these new options yet. [5] So even though alternative fuels are cleaner, they still face problems that need to be solved.

A solar-powered vehicle is a type of vehicle that runs on energy generated from sunlight. It has solar panels, usually placed on the roof or body of the vehicle, which capture sunlight and convert it into electricity. This electricity is then used to power an electric motor that drives the vehicle. [6]

In recent decades, the transportation sector has been a major contributor to global pollution and environmental degradation. Traditional internal combustion (IC) engine vehicles, which run on petrol or diesel, have powered the world for over a century [8,9] However, as the world grapples with climate change, dwindling fossil fuel reserves, and rising health issues due to air pollution, a shift toward sustainable alternatives has become imperative. Among these, solar powered vehicles stand out as a promising and necessary evolution in the automotive industry.

From an economic standpoint, solar vehicles offer long-term cost savings. Although the initial cost of solar cars may be higher due to the advanced technology and materials involved, they have much lower operating and maintenance costs. [9,10] Solar energy is free, and solar cars have fewer moving parts than IC vehicles, which means less wear and tear and fewer repairs. [8]

The push toward solar cars also spurs technological innovation. It promotes the development of more efficient solar panels, better energy storage systems, and lighter, more aerodynamic vehicle designs. These innovations not only benefit the automotive industry but also have applications across various sectors such as renewable energy, aerospace, and consumer electronics. [10].

II. LITERATURE SURVEY

2.1 Tsakalidis et al.: This paper reviews over 270 scientific publications on Solar Electric Vehicles (SEVs) from 1985 to 2023, identifying eight main research areas: solar racing, vehicle design, power train systems, photovoltaic (PV) systems, system integration, control strategies, performance estimations, and market/environmental assessments. SEVs use lithium-ion batteries as the standard due to their energy density and compatibility with EV systems, replacing earlier silver-zinc and nickel-metal hydride types. The range of solar-assisted electric vehicles depends heavily on climate, with solar contribution estimates between 10–18 km/day/k Wp in favorable conditions. Advanced VIPV (vehicle-integrated PV) systems using curved or flexible solar modules can yield 1800 to 5100 km of solar range per year depending on geography. Key technologies include MPPT controllers, in-wheel motors, and lightweight composite bodies. Solar racing events catalyzed innovation but now serve mainly educational roles. PV degradation over time (e.g., >50% in 20 years) and shading effects are significant challenges. Niche vehicles, delivery vans, and urban cars with PV roofs are the most viable markets currently. Real-world data remains limited; most findings are simulation-based. Integration with vehicle control units and grid infrastructure is a future research need. VIPV can reduce battery cycling stress and extend lifespan (up to 19% in buses). SEVs also offer grid resilience benefits in emergencies.

2.2 Solar-Powered Electric Vehicle, IJNRD (April 2023): This project focuses on developing a solar-powered electric vehicle (EV) using photovoltaic (PV) panels as the primary energy source. The PV cells convert sunlight into electricity, which is used to charge 12V batteries—one dedicated to propulsion and another for auxiliary functions like electronics. A DC motor powers the vehicle, and energy is managed using power trackers (likely with MPPT technology) to maintain appropriate voltage levels. The system includes a smart battery with integrated electronics for optimized charging and discharging. The vehicle's range is not explicitly defined, but solar storage enables night time operation using stored energy. The control system uses an Arduino microcontroller and integrates an Android application for wireless control and monitoring via Bluetooth. The vehicle is described as a compact, cost-effective design, suitable for surveillance and remote exploration. Applications include scientific exploration, military operations, search and rescue, and environmental monitoring. The project draws inspiration from NASA's solar-powered rovers and emphasizes intelligent power management. Future upgrades could include IR-based obstacle avoidance and password protection for enhanced security. Overall, it offers a low-cost, eco-friendly alternative to fossil fuel vehicles with minimal maintenance.

2.3 Study of Electric Solar Energy Transmission in Automobile Industry, IRJMETS (Sept 2022): This paper presents a solar-powered electric vehicle concept designed for cost-effective, eco-friendly transportation using a hybrid energy system. The vehicle integrates three charging modes: (1) solar panel-based charging using 200W, 24V photovoltaic cells, (2) plug-in grid charging using a 50–120 kW rapid charger, and (3) regenerative charging via a rotating flywheel mechanism. The primary battery types used are lithium-ion and lead-acid batteries, both of which are rechargeable. A DC motor (6500W, 1HP, 24V, 100A) powers the vehicle, connected to the rear wheels through a chain sprocket. A motor controller intelligently adjusts power flow based on driving conditions to improve efficiency and battery life. The range of the vehicle isn't explicitly stated, but the combination of solar and hybrid systems aims to support extended or continuous travel. A Maximum Power Point Tracker (MPPT) optimizes solar input, while a DC/DC converter manages voltage conversion for auxiliary systems. Applications include industrial transport, urban mobility, and environments where fossil-fuel vehicles are restricted. Despite limitations such as high initial cost and low speed compared to petrol vehicles, the design reduces emissions, noise, and long-term fuel costs. With improvements in solar cell efficiency and battery tech, such systems offer promising future scalability.

2.4 A Review Paper on Solar Electric Vehicles, IRJET (March 2021): This paper provides a comprehensive overview of solar electric vehicles (SEVs), emphasizing their eco-friendliness and potential to reduce reliance on fossil fuels. Solar panels mounted on the vehicle convert sunlight into electrical energy using photovoltaic (PV) cells, which is stored in batteries to power the motor. The vehicle typically uses one of three types of batteries: lead-acid, lithium-ion, and nickel-iron. Lithium-ion batteries are preferred due to their longer life cycles, high energy density, and faster charging capabilities. The electric motor converts stored electrical energy into mechanical energy to drive the vehicle. A power tracker (likely an MPPT) regulates the voltage from the solar array to charge the batteries efficiently. Although exact range is not specified, solar race data referenced shows early vehicles averaging speeds of 67–91 km/h, indicating performance potential. The paper discusses various SEV components like solar arrays, power trackers, inverters, and motors. It emphasizes design considerations, such as maximizing solar exposure and reducing shading. While solar cars have a high initial cost and require significant surface area for solar panels, they offer advantages like zero emissions, silent operation, and minimal fuel costs. The paper sees SEVs as the future of transportation with improvements expected in solar efficiency, battery performance, and vehicle design.

2.5 Solar Powered Vehicle, International Journal of Electrical and Electronics Research (April–June 2015): This paper discusses a solar-powered, four-wheeled, two-seater electric vehicle prototype developed using a 400W solar panel array. The solar panels supply energy to a battery bank comprising four 12V lead-acid batteries connected in series to make 48V. The stored energy powers a 48V DC high torque BLDC motor which drives the wheels through a timing belt pulley mechanism. The system includes a charge controller to regulate battery charging and prevent overcharging or deep discharge, and a boost converter to raise voltage to appropriate levels. Initially, batteries are fully charged and then continuously recharged by the solar panels during operation. The vehicle is designed for short-distance travel with a focus on cost-efficiency and environmental benefits. Though exact range is not provided, the setup supports day use with solar backup. Advantages include low operational cost, zero emissions, and reduced noise. The system avoids slippage due to the toothed pulley design, enhancing transmission efficiency. The project emphasizes solar telemetry for energy monitoring. While limited by the 17% efficiency of standard solar cells, the authors suggest future upgrades using higher-efficiency PV technologies. This model is a step toward cleaner and greener transportation.

2.6 Solar Powered Cars – A Review, IOP Conference Series: Materials Science and Engineering (2021): This review paper explores the design, working principles, and challenges of solar-powered electric vehicles (SEVs), focusing on environmental impact and energy efficiency. SEVs harness energy through photovoltaic (PV) panels mounted on the vehicle surface, converting sunlight into electricity via the photovoltaic effect. This energy is stored in rechargeable batteries, typically lithium-ion, due to their high energy density, efficiency, and long cycle life. The stored energy powers DC or brushless DC motors, enabling vehicle motion. The range of SEVs is not precisely stated but depends heavily on solar irradiance, battery capacity, and motor efficiency—estimated to be viable for short- to medium-range commuting. Key components include solar arrays, charge controllers battery packs, and electric drive systems. The efficiency of typical commercial solar panels is around 17–20%, though newer technologies aim for 30–35%. The study highlights that solar cars face challenges such as high initial cost, energy conversion limits, and dependency on weather conditions. Despite this, they offer advantages like zero emissions, low operational cost, and minimal noise. Solar-powered cars have strong potential in sustainable urban mobility, especially as battery and PV tech improves. The paper emphasizes that continued innovation and cost reduction are essential for widespread adoption.

III. CONCLUSION

Solar vehicles hold significant promise as a sustainable solution to the growing global concerns over fossil fuel depletion, environmental pollution, and rising energy demands. With advancements in photovoltaic (PV) cell efficiency, battery technologies (mainly lithium-ion), and lightweight vehicle design, solar vehicles are evolving from experimental concepts into viable transportation options. While current limitations like limited solar range, weather dependency, and high costs restrict mainstream adoption, ongoing innovations and economies of scale are expected to reduce these barriers. In the future, vehicle-integrated photovoltaics (VIPV) will likely become standard features on electric vehicles, serving as supplementary energy sources for extended range or auxiliary power. The most practical applications in the near term include urban commuting, last-mile delivery, and off-grid mobility in sunny regions. Moreover, integration with smart grids, energy storage, and autonomous systems may allow solar vehicles to become energy-positive assets, contributing back to the grid. In conclusion, while solar vehicles may not completely replace conventional EVs, they will play a critical role in decarbonizing transport, reducing energy costs, and enabling clean, resilient mobility in a renewable-powered future.

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Utilization of Waste Plastic in the Fabrication of Sustainable Bricks : A Comparative Study on Strength and Feasibility

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ABSTRACT

The ever-increasing accumulation of plastic waste has emerged as a critical environmental concern, largely due to its non-biodegradable nature and hazardous effects on ecosystems. To address this issue sustainably, the conversion of waste plastic into construction bricks offers a promising alternative to conventional waste disposal methods. This paper highlights the potential applications of plastic bricks across various sectors. These bricks, made by thermally processing and molding waste plastics, exhibit durability, water resistance, and thermal insulation properties. They can be effectively used in non-load-bearing construction such as pathways, garden walls, temporary shelters, road paving blocks, and low-cost housing components. Moreover, their lightweight nature and resistance to moisture make them ideal for use in coastal or flood-prone regions. By integrating plastic bricks into mainstream construction, this solution not only reduces environmental pollution but also supports the development of low-carbon, sustainable infrastructure.

Keywords: Waste Plastic Bricks, Eco-friendly Building Materials, Circular Economy, Hazardous Waste Utilization, Low-cost Housing, Environmental Sustainability, Recycled Plastic

I. INTRODUCTION

Plastic, known for its light weight, versatility, and durability, has become one of the most extensively used materials in the modern world. From packaging and containers to everyday household items, its presence is ubiquitous. However, the very properties that make plastic desirable—its resilience and resistance to degradation—also pose serious environmental challenges. Globally, over 300 million tonnes of plastic waste are generated each year, and in India alone, municipal solid waste is projected to exceed 70 million tonnes annually by 2025, with plastic contributing a significant and growing share.

The non-biodegradable nature of plastic polymers prevents them from decomposing naturally, often persisting in the environment for hundreds to thousands of years. Factors such as rapid urbanization, population growth, and rising consumerism have significantly increased the per capita plastic consumption and waste generation. Traditional disposal techniques like landfilling and incineration not only fail to resolve the problem but also introduce new environmental hazards, including groundwater contamination and toxic emissions.

In response, the construction industry has begun exploring alternative, sustainable materials that align with circular economy principles. One such innovation is the conversion of waste plastic into plastic bricks—a promising solution that combines waste management with sustainable building practices. These bricks are created through thermal processing and molding of waste plastics, producing a lightweight, durable, and water-resistant building material.

A key area of interest is the comparison between conventional burnt clay bricks and plastic bricks, particularly in terms of compressive strength:

TABLE I

Parameter	Burnt Clay Brick	Plastic Brick (from waste)
Average Compressive Strength	3.5 MPa – 10.5 MPa (IS 1077:1992)	8MPa – 12 MPa (based on recent trials)
Water Absorption	15% – 20%	0.9%-1.2%
Weight	Heavier	Lighter (30–40% reduction)
Environmental Impact	High (requires topsoil & energy)	Low (made from recycled waste)
Thermal Insulation	Moderate	High

II. LITERATURE REVIEW

Sharma & Bansal (2021) – Utilization of Waste Plastic in Manufacturing of Bricks

This study investigated the use of shredded plastic waste blended with sand to produce construction bricks. Results showed compressive strengths ranging from 7 to 10 MPa and minimal water absorption, making them a promising alternative to conventional bricks under specific conditions.

Kumar et al. (2020) – Evaluation of LDPE-Based Plastic Bricks

The authors examined the structural behavior of bricks made by melting LDPE plastic waste and mixing it with quarry dust. Their findings reported compressive strength values around 9.2 MPa and low water absorption, indicating strong durability and weather resistance.

Reddy & Prakash (2019) – Mechanical Properties of Bricks Using PET and HDPE Waste

This research focused on the compressive and thermal behavior of bricks developed from HDPE and PET plastic waste. The bricks achieved strength above 10 MPa and displayed excellent resistance to moisture, suggesting suitability for exterior wall applications.

Mohan & Devi (2021) – Sustainable Use of Plastic in Brick Production

The paper reviewed the potential of using plastic as a binder in eco-bricks. It concluded that these bricks not only reduce plastic waste accumulation but also provide a low-cost alternative to traditional clay bricks with comparable strength.

Ali et al. (2018) – Performance of Plastic-Sand Composite Bricks

Researchers developed composite bricks using polypropylene plastic and river sand. Laboratory tests showed compressive strengths up to 11 MPa, low permeability, and high thermal insulation, supporting their use in energy-efficient buildings.

Singh & Jaiswal (2022) – Conversion of PET Bottles into Structural Bricks

The study explored recycling PET bottles into lightweight construction bricks. The experimental results revealed compressive strength exceeding 8 MPa and significant reductions in overall material weight, ideal for prefabricated or partition wall systems.

Das & Ghosh (2020) – Technical Comparison of Clay Bricks and Plastic Bricks

This comparative analysis focused on material performance, cost, and sustainability. Plastic bricks were found to be 20–30% less expensive, 40% lighter, and capable of achieving average strength around 9 MPa, with enhanced resistance to water damage.

Karthikeyan & Raj (2019) – Integrating Municipal Plastic Waste into Brick Manufacturing

The paper assessed how urban plastic waste can be repurposed into bricks. It emphasized that using locally available plastic reduces waste load, lowers material costs, and meets basic construction requirements.

Mehta & Patel (2023) – Hybrid Bricks from Plastic Waste and Fly Ash

The study combined plastic waste with fly ash to create eco-friendly construction bricks. These hybrid bricks reached strengths above 10 MPa and showed improved resistance to high temperatures, making them suitable for harsh environmental conditions.

Nair & Thomas (2021) – Environmental and Structural Assessment of Plastic Bricks

This work examined plastic bricks in terms of life-cycle benefits and structural use. Results indicated improved durability, reduced carbon emissions, and potential application in green-certified construction projects.

III. METHODS AND MATERIAL

Objective

The primary aim of this study is to recycle waste plastic by manufacturing plastic bricks, thereby addressing environmental concerns such as land and water pollution caused by improper disposal of plastics. By transforming waste plastic into a cost-effective construction material, this work explores sustainable alternatives to conventional clay bricks. The study also includes a comparative analysis of strength and cost between traditional clay bricks and recycled plastic bricks by varying the proportion of plastic content. The objective is to identify the optimal plastic percentage that yields the best performance in terms of both strength and economic viability.

Specifications

The materials used in the production of plastic bricks are detailed below along with their relevant physical properties.

A. Fine Aggregate – Sand

River sand is employed as a fine aggregate in the brick-making process. The physical properties were determined in accordance with IS 2386 (Part I), and the sand was confirmed to fall under Zone III grading as per IS 383:1970.

TABLE III

Sl. No.	Property	Test Method/Standard	Value
1	Specific Gravity	IS 2386 (Part III)	2.66
2	Bulk Density	IS 2386 (Part III)	1687 kg/m³
3	Fineness Modulus	IS 2386 (Part I)	2.49

B. Waste Plastic

Plastic waste is collected from common domestic and commercial sources such as bottles, packaging materials, bags, and containers. The reason for the extensive use of plastics lies in their lightweight nature, chemical resistance, durability, and excellent thermal and electrical insulation properties. The classification of plastic types used in this study, along with their typical recycling statistics, is provided below.

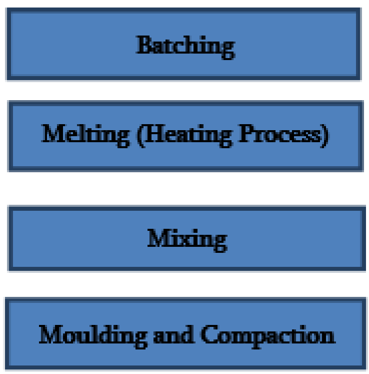
TABLE IIIII

Sl. No.	Type of Plastic	Common Sources	Form Used	Estimated Recycling Rate
1	PET (Polyethylene Terephthalate)	Beverage bottles, oil containers	Shredded flakes	~25%
2	HDPE (High-Density Polyethylene)	Detergent containers, shampoo bottles	Granules	~30–35%
3	PVC (Polyvinyl Chloride)	Pipes, window frames, medical disposables	Chopped pieces	~1–2%
4	LDPE (Low-Density Polyethylene)	Grocery bags, film wraps, milk pouches	Pellets	~10–15%
5	PP (Polypropylene)	Food containers, bottle caps, medicine wrappers	Crushed form	~20%

IV. Mixing and Methodology

The production of plastic bricks involves a systematic process consisting of four key stages: batching, melting, mixing, and moulding. Experimental trials were conducted with two mix proportions: 1:2 and 1:3 by weight (plastic to sand), to determine the optimal blend for strength and durability.

Fig. 1: Stages of Plastic Brick Manufacturing



A. Batching

The plastic waste collected from various domestic and industrial sources is first cleaned thoroughly and sun-dried to eliminate moisture and impurities. The material is then weighed using a digital balance. Meanwhile, river sand is sieved using a 600-micron sieve to ensure uniform particle size.

For the experimental setup, two mixing ratios were prepared:

Mix A (1:2) – 1 kg of plastic with 2 kg of sand

Mix B (1:3) – 1 kg of plastic with 3 kg of sand

B. Melting (Heating Process)

Melting is a critical step requiring controlled heat. The pre-weighed plastic is placed inside a steel drum positioned in a closed combustion pit constructed with fire-resistant bricks to limit environmental emissions. The temperature is gradually increased until the plastic transitions to a viscous molten state (around 150–180°C depending on the plastic type).

Care must be taken not to overheat, as excessive heat can degrade the polymer and form harmful gases.

The use of a cover or lid helps retain heat and control emissions.

C. Mixing

Once the plastic is adequately molten, sieved sand is slowly added into the molten plastic in the required proportion. Mixing is performed manually using steel paddles or mechanically for larger batches.

Mixing Duration: 5 to 7 minutes, ensuring even distribution of sand throughout the plastic matrix.

Precautions: The operator must wear protective gloves, goggles, and masks due to heat and fumes.

The blend should form a consistent, semi-solid composite ready for moulding.

D. Moulding and Compaction

The hot composite is poured into standard brick moulds of dimensions 190 mm × 90 mm × 90 mm. Compaction is done using a tamping rod to eliminate air pockets and improve density.

After compaction, bricks are allowed to air cool for 24 hours.

No water curing is required, as plastic solidifies on cooling and binds the sand mechanically.

V. RESULTS AND DISCUSSION

After the moulding process, the plastic bricks were allowed to cool and set for 24 hours at room temperature. This curing period facilitates better bonding between the molten plastic and the sand particles. A series of laboratory tests were then conducted to assess the mechanical and physical performance of the bricks.

The key tests performed are as follows:

A. Compressive Strength Test

B. Hardness and Impact Resistance Test

C. Additional Tests (Fire Resistance & Soundness)

A. Compressive Strength Test

The compressive strength test was conducted using a Compression Testing Machine (CTM). Each specimen was placed centrally on the machine's platform, and load was applied uniformly at a constant rate until failure occurred. The aim was to determine the maximum compressive stress the bricks could withstand.

Table IV: Compressive Strength of Plastic Bricks

Sl. No.	Plastic-to-Sand Ratio	Average Compressive Strength (N/mm^2)

1	1:3	7.20
2	1:2	9.10

Observation: Bricks with a 1:2 ratio (higher plastic content) exhibited superior compressive strength, indicating better bonding and structural integrity.

B. Hardness and Impact Resistance Test

The surface hardness and impact durability of the bricks were assessed using two methods:

Scratch Test: A steel rod was used to apply pressure and attempt to scratch the surface.

Drop Test: Bricks were dropped from two different heights onto a hard concrete surface to simulate accidental impact.

Table V: Hardness and Impact Resistance Results

Sl. No.	Plastic-to-Sand Ratio	Drop Height	Result
1	1:2	6 ft	No Surface Damage
2	1:3	10 ft	Minor Corner Chipping

Observation: Bricks with higher sand content (1:3) showed minor edge damage at greater height, but no structural failure was observed in either case.

C. Additional Observations

Fire Resistance Test: The bricks were exposed to elevated temperatures using a blowtorch. Initial cracking occurred between 110–130°C, indicating moderate fire resistance. Prolonged exposure caused surface deformation.

Soundness Test: Two-day-old bricks were struck against each other. A sharp metallic sound was noted, suggesting good internal bonding and low porosity.

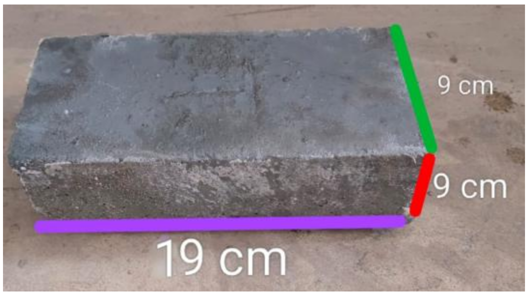


Figure 1: Plastic Bricks

VI. CONCLUSION

The experimental study successfully demonstrates that waste plastic can be effectively utilized in the production of plastic bricks, offering a sustainable and eco-friendly alternative to conventional clay bricks. The process not only contributes to solid waste management by reducing plastic pollution but also yields a durable and cost-effective construction material.

Among the tested ratios, bricks manufactured with a 1:2 plastic-to-sand mix exhibited higher compressive strength (9.10 N/mm^2) and superior hardness, making them more suitable for non-load-bearing structural applications. While the 1:3 ratio also produced acceptable results, it showed relatively lower strength and slight surface damage during impact testing.

However, the fire resistance of these bricks remains limited, as deformation and cracking begin at temperatures above 110°C. Despite this, the soundness test confirmed strong bonding between the materials, as evidenced by a clear metallic ring upon striking.

In conclusion, plastic bricks—especially those made with a 1:2 mix ratio—offer a promising solution for waste management and low-cost construction. Further research is recommended to enhance fire resistance and evaluate long-term performance under environmental exposure.

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Biodiesel Blends and Engine Performance Analysis Using Python Programming : A Review

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ABSTRACT

This review paper gives a comprehensive analysis of the effects of biodiesel derived from corn oil, palm oil, and waste cooking oil on diesel engine performance and emissions. Synthesizing findings from peer-reviewed studies since 2000, it examines key metrics such as brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), power output, and emissions including carbon monoxide (CO), hydrocarbons (HC), particulate matter (PM), and nitrogen oxides (NOx). The paper highlights the application of Python programming for data analysis and visualization, demonstrating its utility in processing complex engine performance datasets. Results indicate that biodiesel blends generally reduce emissions such as CO, HC, and PM emissions but may increase NOx, with variations depending on feedstock and blend ratio. Engine performance is slightly compromised, with lower BTE and higher BSFC compared to diesel. The review discusses challenges such as feedstock sustainability and proposes future research directions to optimize biodiesel use. This work aims to inform engineers, researchers, and policymakers about biodiesels potential such as an alternative sustainable fuel.

Keywords: Biodiesel, Engine Performance, Emissions, Corn Oil, Palm Oil, Waste Cooking Oil, Python Data Analysis

I. INTRODUCTION

1.1 BACKGROUND ON BIODIESEL

Biodiesel, a renewable and biodegradable fuel, is produced from vegetable oils, animal fats, or recycled restaurant grease through the chemical process also known as transesterification. This process involves reacting fats or oil with an alcohol, typically methanol, in the presence of a catalyst to produce something called fatty acid methyl esters (FAME) as well as glycerin as by-product [1]. Biodiesel is a viable alternative to petroleum diesel, offering a sustainable energy source that can be used in compression-ignition engines with minimal modifications [2]. Its adoption is driven by the need to reduce greenhouse gas emissions, decrease dependence on fossil fuels, and manage waste products like used cooking oil, contributing to a circular economy.

1.2 ADVANTAGE OF BIODIESEL

Biodiesel offers several environmental and economic benefits. It is biodegradable and produces fewer pollutants such as sulfur oxides and particulate matter compared to diesel [3]. Its higher cetane number enhances combustion efficiency, reducing engine knock and improving performance [2]. Economically, biodiesel can be produced domestically, supporting local agriculture and reducing reliance on imported oil [4]. Additionally, biodiesels lubricity can extend engine life by reducing wear on engine components [5].

1.3 CHALLENGES AND RESEARCH NEEDS

Despite its advantages, biodiesel presents challenges that necessitate further research. Its lower energy content (approximately 10-12% less than diesel) can lead to increased fuel consumption and reduced power output [3]. While biodiesel does reduces emissions of CO, HC, and PM, it often increases NOx emissions, which contributes to air pollution [6]. These effects vary depending on the feedstock and blend ratio, making it critical to study different biodiesel sources. Mainly feedstocks such as corn oil, palm oil, and waste cooking oil are of particular interest due to their high availability and distinct properties.

1.4 FEEDSTOCKS FOR BIODIESEL

Biodiesel feedstocks are categorized into edible oils (e.g., soybean, palm), non-edible oils (e.g., jatropha, pongamia), and waste oils (e.g., used cooking oil). Edible oils raise concerns about food security and land use, prompting interest in non-edible and waste oils [7]. Corn oil, the by-product of ethanol production, is abundant in regions like the United States [8]. Palm oil, known for its high yield and low cost, is widely used in Southeast Asia [9]. Waste cooking oil offers a cost-effective and environmentally beneficial option by recycling waste [10].

1.5 OBJECTIVE AND SCOPE

This review aims to: 1. Provide an overview of biodiesel production and properties from corn oil, palm oil, and waste cooking oil. 2. Summarize the effects of these biodiesels on diesel engine performance and emissions based on recent research. 3. Demonstrate the use of Python programming in analyzing engine performance data. 4. Identify research gaps and propose future directions for biodiesel optimization.

The paper focuses on studies published since 2000, emphasizing experimental data on BTE, BSFC, power, torque, and emissions. It also highlights Pythons role in data analysis, offering insights into its practical applications.

II. LITERATURE REVIEW

2.1. GENERAL EFFECTS OF BIODIESEL ON THE ENGINE PERFORMANCE

Biodiesels impact on the engine performance is evaluated through metrics as BTE, BSFC, power output and torque. BTE, which measures the efficiency of the converting fuel energy into mechanical work, is typically slightly lower for biodiesel blends due to the lower calorific value. For example, Saini et al. (2020) reported that corn oil methyl ester (COME) B10 had a BTE of 33.98%, marginally lower than diesel [8]. McCarthy et al. (2011) observed similar reductions for blends derived from tallow and canola oil [11].

BSFC, the fuel consumed per unit of the power, is higher for biodiesel cause of its lower energy content. Saini et al. (2020) found BSFC increases of 2% for B10, 4% for B20, and 6% for B30 corn oil blends [8]. Power and torque are generally lower, attributed to higher viscosity and poorer atomization [11]. A study on various blends reported a 10-12% reduction in brake power for 100% palm biodiesel at full load [12].

2.2. GENERAL EFFECTS ON EMISSIONS

Biodiesels emission profile is a key factor in its adoption. It typically reduces CO, HC, and PM , the emissions due to its oxygen content, which thus promotes complete combustion. Al- Dawody et al. (2012) reported reductions of 18.6% in CO and 26.7% in HC for B20 waste cooking oil biodiesel [10]. PM emissions also decrease, with corn oil biodiesel reducing smoke opacity by up to 10% [8].

NOx emissions, however, often increase due to higher combustion temperatures and advanced injection timing. A study on biodiesel blends found a 45.21% increase in NOx for B100 at low load [13]. However, some feedstocks, like palm oil, may show lower NOx under specific conditions [14].

2.3. EFFECTS OF SPECIFIC FEEDSTOCKS

2.3.1 CORN OIL BIODIESEL

Corn oil biodiesel, derived from ethanol production by-products, is a promising feedstock. Saini et al. (2020) found that B10 COME had a BTE of 33.98%, with BSFC increasing by 2-6% across blends. Emissions showed reduced CO and HC but variable NOx, with some studies reporting decreases [8]. Another study noted increased HC and smoke but lower NOx, suggesting variability due to engine conditions or fuel properties [15].

2.3.2 PALM OIL BIODIESEL

The palm oil biodiesel benefits from high cetane number, enhancing combustion efficiency. Arbab et al. (2017) noted improved BTE for palm oil blends, though BSFC was higher [9]. Emissions typically include lower CO, HC, and PM, with NOx varying. One study reported a 28% reduction in CO for PO100 at 1200 rpm and lower NOx compared to diesel [14], contrasting with general trends of increased NOx.

2.3.3 WASTE COOKING OIL BIODIESEL

The waste cooking oil biodiesel is cost-effective and sustainable. Al-Dawody et al. (2012) found lower thermal efficiency and higher BSFC for WCO blends, with reductions in CO (18.6%), HC (26.7%), and PM but increased NOx [10]. Another study confirmed that higher `CO2 and NOx but lower CO and HC [16].

2.4. PYTHON IN DATA ANALYSIS

Python is widely used in engineering research for data processing and visualization. Li- braries like Pandas, Matplotlib, and Scipy enable efficient analysis of engine performance data. For example, Python can generate plots of BTE versus load or perform ANOVA to compare fuel types. A study used Python to visualize corn oil biodiesel data, showing B20 blends perform similarly to diesel at low loads [8].

III. METHODOLOGY

31. LITERATURE COLLECTION

This review synthesizes data from peer-reviewed studies published between 2000 and 2023, sourced from Science Direct, PubMed, and Google Scholar. Keywords included biodiesel, engine performance, emissions, corn oil, palm oil, waste cooking oil, and Python data analysis. Studies were selected for their focus on experimental data related to BTE, BSFC, power, torque, and emissions.

32. DATA ANALYSIS APPROACH

The review compiles quantitative data from experimental studies, focusing on biodiesel blends (e.g., B10, B20, B100). Pythons role in data analysis is highlighted, with example code demonstrating data processing and visualization:

```
import pandas as pd
import matplotlib.pyplot as plt

# Load dataset
data = pd.read_excel('biodiesel_data.xlsx')

# Filter for specific load
load_50 = data[data['load'] == 50]

# Plot BTE for each blend
blends = load_50['blend'].unique()
for blend in blends:
    subset = load_50[load_50['blend'] == blend]
    plt.plot(subset['load'], subset['BTE'], label=
        blend)

plt.xlabel('Engine Load (%)')
plt.ylabel('Brake Thermal Efficiency (%)')
plt.title('BTE vs. Load for Biodiesel Blends')
plt.legend()
plt.savefig('bte_comparison.png')
```

Fig 1: Code 1

This code loads engine data, filters for a specific load, and plots BTE, illustrating Pythons utility in biodiesel research.

33. COMPARATIVE ANALYSIS

Data from different feedstocks were compared using tables and statistical insights. For example, ANOVA can be applied to test significant differences in BTE:

```
# Load datasets for different biodiesels
come_data = pd.read_excel('come_data.xlsx')
pome_data = pd.read_excel('pome_data.xlsx')
wcome_data = pd.read_excel('wcome_data.xlsx')


# Filter for B20 blend and 50% load

come_b20_50 = come_data[(come_data['blend'] == '
    B20') & (come_data['load'] == 50)]

pome_b20_50 = pome_data[(pome_data['blend'] == '
    B20') & (pome_data['load'] == 50)]

wcome_b20_50 = wcome_data[(wcome_data['blend'] ==
    'B20') & (wcome_data['load'] == 50)]


# Calculate average BTE

bte_values = [come_b20_50['BTE'].mean(),

    pome_b20_50['BTE'].mean(), wcome_b20_50['BTE'
    ].mean()]

biodiesels = ['COME', 'POME', 'WCOME']


# Plot

plt.bar(biodiesels, bte_values)
plt.xlabel('Biodiesel Type')

plt.ylabel('Average BTE (%) at 50% Load for B20')
plt.title('BTE Comparison Across Biodiesels')

plt.savefig('bte_biofuels.png')
```

Fig 2: Code 2

This code compares the average BTE for B20 blends of different biodiesels at 50% load.

IV. RESULT AND DISCUSSION

4.1. ENGINE PERFORMANCE COMPARISON

Table 1 summarizes performance metrics for biodiesel from different feedstocks. Palm oil biodiesel shows slightly better BTE, likely due to its higher cetane number. BSFC is consistently higher for all biodiesels, reflecting their lower energy content.

TABLE I

Engine Performance Comparison for B20 Blends

Feedstock	BTE (%)	BSFC (g/kWh)	Power Output	Torque
Diesel	15-18	200-250	Baseline	Baseline
Corn Oil	12-15	250-300	Slightly lower	Slightly lower
Palm Oil	13-16	240-290	Comparable	Comparable
Waste Cooking Oil	12-14	260-310	Slightly lower	Slightly lower

4.2. EMISSION CHARACTERISTICS

TABLE II

Compares emissions for B20 blends

Feedstock	CO	HC	PM	NOx
Diesel	Baseline	Baseline	Baseline	Baseline
Corn Oil	Lower	Lower	Lower	Variable
Palm Oil	Lower	Lower	Lower	Lower/Variable
WasteCooking Oil	Lower	Lower	Lower	Higher

Biodiesel reduces CO, HC, and PM emissions due to its oxygen content. NOx emis- sions vary, with waste cooking oil typically showing increases, while corn and palm oil results are inconsistent, possibly due to differences in fatty acid composition or engine settings.

4.3. PYTHON ANALYSIS INSIGHTS

Python visualizations reveal that B20 blends perform comparably to diesel at low loads but lag at higher loads. Statistical tests like ANOVA confirm significant differences in performance metrics, aiding in fuel optimization.

V. DISCUSSION

The trade-offs between environmental benefits and performance challenges are evident. Biodiesels lower energy content reduces efficiency, but its emission reductions are signif- icant. Variability in NOx emissions suggests the need for tailored engine calibrations or additives to mitigate increases [17].

VI. CHALLENGES AND FUTURE PROSPECTS

5.1 SUSTAINBILITY CONCERNS

First-generation biodiesels like palm oil compete with food production, raising concerns about land use and deforestation [18]. Waste cooking oil and non-edible oils offer more sustainable alternatives.

5.2 TECHNOLOGICAL ADVANCEMENTS

The innovations in production, such as the enzymatic transesterification, could reduce costs and improve biodiesel quality [19]. Engine modifications or additives may address NOx in- creases.

5.3 POLICY SUPPORT

Policies like the Renewable Fuel Standard promote biodiesel use through mandates and incentives [20]. Continued support is crucial for scaling production and adoption.

VII. CONCLUSION

Biodiesel from the corn oil, palm oil and waste cooking oil offers environmental benefits by reducing CO, HC and PM emissions, but it compromises engine performance with lower level of BTE and higher BSFC. NOx emissions vary, necessitating further research into feedstock-specific effects. Python programming enhances data analysis, providing clear insights into fuel performance. Future research should focus on sustainable feedstocks, advanced production methods, and engine optimizations to maximize biodiesels potential as a renewable fuel.

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Advancing Technologies and Strategies for Achieving Carbon Neutrality

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ABSTRACT

Since the Industrial Revolution, natural resource overexploitation—through deforestation, the burning of fossil fuels, and land use changes—has driven global development and increased GHG levels by considerable amounts. Human activities have mainly caused climate change, and attaining carbon neutrality in 2050 is a global goal. This requires widespread industrial process reforms to reduce emissions and increase CO_2 removal. Here, we talk about the latest technologies that make carbon neutrality and sustainable development possible, including waste valorization, conservation of carbon sinks, food system change, renewable energy generation, and negative-emission manufacturing.

Keywords: Carbon neutrality; renewable energy; carbon sequestration; carbon capture and utilization; carbon footprint reduction; climate change mitigation.

I. INTRODUCTION

Technological Innovation in the Quest for Carbon Neutrality

The growing urgency of climate change has catapulted carbon neutrality—the offsetting of CO_2 emissions by their capture—onto the world agenda. Achieving it will take a multidisciplinary approach coupling technological advancement, sustainable stewardship, and strong policy support [1]. Technologies for renewable energy are at the center of the effort, offering cleaner alternatives to fossil fuels by harnessing solar, wind, water, and biomass power [2, 3]. Increased solar PV, CSP, wind power, and hydropower have raised efficiency and access levels significantly [4, 5, 6], while innovations such as floating solar, hybrid facilities, tidal and wave energy, green hydrogen, and geothermal power expand the choice for clean energy further [7, 8, 9]. Parallelly, CCUS technologies like direct air capture, BECCS, and CCU are major tools for removing CO_2 from or reusing it, allowing a circular carbon economy [1]. Parallel solutions like enhancing energy efficiency, growing electric mobility, and enabling climate-smart agriculture are also pivotal [1,10]. Finally, international cooperation, ambitious policy, and public engagement remain needed to accelerate low-carbon development [1]. This article discusses such technologies, their mode of operation, impacts, and implementation challenges towards achieving carbon neutrality and also show the optimal energy usage through resilient and green power supply refer to Figure 1.

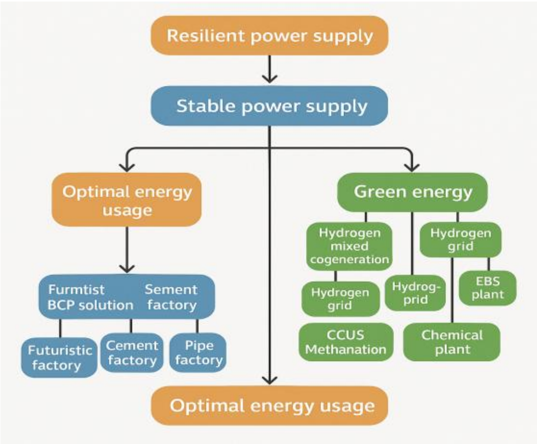

Figure 1: Flow Chart of Optimal Energy Usage Through Resilient and Green Power Supply

II. LITERATURE REVIEW

Wang et al. (2021) give an exhaustive analysis of the available technologies and strategic avenues for realizing carbon neutrality. They highlight integrating renewable energy, electrification of end-use sectors, negative emissions technologies, and policy frameworks as the essential pillars. The study also identifies systems thinking and cross-sectoral coordination as necessary measures to overcome economic and technical constraints.

Luderer et al. (2019) explore environmental co-benefits and side effects of various strategies to decarbonize the power sector. Their discussion highlights the complexity of transitions, where decarbonization is shown to strongly decrease air pollution and enhance public health but some strategies can result in land-use conflicts or raised resource requirements. Their multi-model comparison increases the strength of results for various scenarios mentioned in Table 1.

Table 1: Environmental Co-benefits vs. Adverse Effects (Source from Luderer et al., 2019)

Decarbonization Strategy	**Co-benefits**	**Adverse Side-effects**
Renewable Integration	Reduced air pollution, jobs	Land use, grid stress
Electrification	Efficiency, health benefits	Infrastructure cost
Bioenergy	Emission reduction	Deforestation, water use
Nuclear	Low emissions	Waste disposal, safety concerns

Jacobson et al. (2015) offer one of the most powerful global models for a 100% clean and renewable wind, water, and sunlight (WWS) energy transition. Their 139-country roadmap shows the technical viability of such a transition by 2050, promoting electrification and efficiency gains in all energy sectors. The research strongly confirms the socioeconomic and environmental advantages of a WWS-based system, such as job creation and lower energy costs.

IRENA (2020) provides real-world data on the decreasing costs of renewable power technologies, highlighting the fact that solar and wind hit a record-low levelized cost of electricity (LCOE) in 2019. This cost competitiveness further bolsters the argument for renewables as cost-effective substitutes for fossil fuels, particularly for emerging markets.

Zappa, Junginger, and van den Broek (2019) analyse the viability of a completely renewable European power system in 2050 and find that the system is technically feasible but calls for significant investments in infrastructure, cross-border collaboration, and energy storage. Sector coupling and flexible demand management are identified by them as central enablers for system stability.

Kost et al. (2018) of Fraunhofer ISE present elaborate LCOE estimates of different renewable technologies in favor of the economic case of solar PV and onshore wind as the least-cost sources. Their work is beneficial in techno-economic planning as it provides evidence-based information on cost trends and location differences.

Bogdanov et al. (2019) suggest a stepwise transition path towards a sustainable electricity system based on a global modelling framework. Their results highlight the capability of regional optimization in conjunction with a globally integrated system to provide a cost-effective and secure renewable power supply even under rising electricity demand.

Hansen, Breyer, and Lund (2019) present a review of 100% renewable energy systems' present status and future outlook in support of holistic energy planning. Systemic innovation such as storage technologies, sector integration, and socio-political participation is needed for a complete transition.

Table 2: Summary of Reviewed Studies On Carbon Neutrality and Renewable Energy

Sl No.	Reference	Focus Area	Key Contributions	Methodology
1	Wang et al. (2021)	Carbon Neutrality Pathways	Overview of technologies, electrification, negative emissions	Policy and technology review
2	Luderer et al. (2019)	Power Sector Decarbonization	Co-benefits, side-effects, environmental impacts	Multi-model comparison
3	Jacobson et al. (2015)	100% Renewable Energy Roadmap	WWS-based global energy roadmap for 139 countries	Simulation-based modeling
4	IRENA (2020)	Cost of Renewables	Declining global cost trends in solar, wind	Empirical analysis
5	Zappa et al. (2019)	EU Power System Feasibility	Renewable EU grid feasibility by 2050	Energy system modeling
6	Kost et al. (2018)	LCOE of Renewable Technologies	Techno-economic analysis of solar, wind LCOE	Techno economic modeling
7	Bogdanov et al. (2019)	Global Renewable Transition	Evolutionary pathway to sustainable electricity	Optimization modeling
8	Hansen et al. (2019)	100% RE Systems Review	State-of-the-art and perspectives	Literature review

III. SOLAR ENERGY TECHNOLOGIES

Solar power is at the heart of the world's move toward clean, renewable energy, providing a fossil-fuel-free alternative and enabling carbon neutrality [11]. Photovoltaic (PV) systems, Concentrated Solar Power (CSP), and solar thermal systems are the key technologies [22]. PV systems convert sunlight into electricity directly by employing silicon-based semiconductors [13], with panel varieties being high-efficiency monocrystalline [14], low-cost polycrystalline [15], and thin-film panels [16] with light weight. New technologies such as perovskite cells [17], bifacial panels [18], and floating solar farms [19] are boosting performance and functionality. CSP systems employ mirrors to focus sunlight into heat, which produces steam to power turbines [20]. Their capacity to store heat in molten salts allows power generation even without sun [21]. Solar thermal systems collect solar heat for domestic, commercial, and industrial use [12], including water heating [23] and high-temperature industrial processes [24]. Innovations such as building-integrated photovoltaics (BIPV), solar tracking systems [18], energy storage [17], and Agri voltaic [19] are opening up new possibilities for solar. With decreasing costs—more financing 80% in the last ten years [16] solar is increasingly affordable and a rising source of clean energy and jobs [22]. In sum, ongoing innovation and investment in solar power are key to a sustainable, carbon-free future [11].

Solar Thermal Energy

Solar thermal energy (STE) is a renewable energy technology that captures energy from the sun to produce thermal energy. This heat is utilized for different applications, such as water heating, space heating, industrial processes, and electricity generation. Solar thermal systems differ from solar photovoltaic (PV) systems, which directly convert sunlight into electricity, in that solar thermal systems utilize sunlight to generate heat, which can be stored and then converted into useful energy referred to Figure 2.

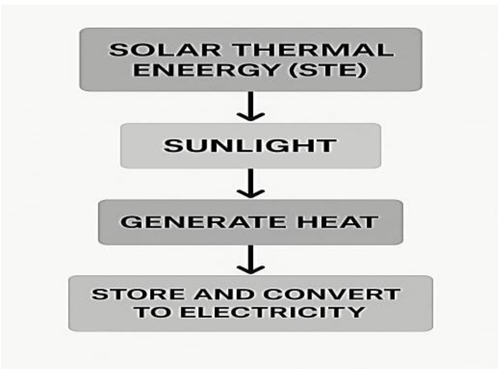

Figure 2: Steps of Solar Thermal Energy

Working Principle of Solar Thermal Energy

Three principle steps are used in the solar thermal energy process. Solar collectors or mirrors capture sunlight and transmit it as heat in the process of solar radiation collection. Thereafter, transfer and storage of the produced heat is done utilizing a heat medium like water, oil, or molten salt. Lastly, in the final stage of energy utilization, either the stored heat is utilized to provide heating service directly or steam turbines are driven to produce electricity.

Types of Solar Thermal Energy Systems

Solar thermal systems are divided according to operating temperature into low-, medium-, and high-temperature systems, with different applications and technologies.

Low-Temperature Systems (Less Than 100°C)

Are employed for residential, commercial, and industrial space heating. Applications are solar water heating (with flat-plate or evacuated tube collectors), space heating (through radiators or underfloor systems), solar air heating (for crop drying and ventilation), and solar cooling (with absorption chillers). Technologies are Flat-Plate Collectors (FPC) and more effective Evacuated Tube Collectors (ETC) for lower-temperature locations.

Medium-Temperature Systems (100–250°C)

Supply industries such as food processing, textiles, and chemicals. They deliver industrial process heat (for drying, sterilizing, chemical reactions) and enable solar cooking with concentrated sunlight. The main technology is the Parabolic Trough Collector (PTC).

CSP Employs High-Temperature Systems (Over 250°C)

To generate electricity by concentrating sunlight to produce steam. CSP technologies are PTCs (employed in facilities such as Spain's Andasol), Solar Power Towers (heliostats concentrate sunlight on a central receiver, e.g., Ivanpah in the USA), Linear Fresnel Reflectors (LFR) (flat mirrors concentrating sunlight at lower cost), and Solar Dish/Engine Systems (parabolic dishes powering Stirling engines for small-scale, high efficiency power).

Solar Thermal Energy: Benefits, Challenges, and Future Directions

Solar thermal energy is cost-effective, abundant, and very efficient in regions abundant in sunlight. It is particularly applicable in heating water, space, and industrial processes. One of its advantages lies in the capability to store thermal energy (e.g., in molten salt), which allows it to generate electricity even without direct sunlight. It also helps to combat greenhouse gas emissions and can be made available from the scale of a single building to the scale of utilities. But solar thermal systems, especially Concentrated Solar Power (CSP), have their own set of challenges including high upfront capital expenditures, extensive land and water demands, and reliance on location and sunlight exposure. They are not necessarily dependable as baseload resources and usually need fossil fuel back-up. CSP systems are even mechanically intensive, in need of specialized maintenance and slower start-ups than solar PV. In the future, developments in solar thermal energy focus on increasing efficiency, sustainability, and flexibility. Hybrid systems that integrate solar thermal with PV or fossil fuel provide steadier energy output. Thermal storage technologies are becoming more efficient and cost-effective. Solar thermal power plants floating on water decrease land use, while solar desalination is a sustainable alternative for addressing water shortages. In addition, the convergence of AI and smart control systems is improving performance by intelligent tracking and automation.

IV. WIND ENERGY

Wind, powered by the unequal heating of the Earth's surface by the Sun, is an indirect solar energy and a key to carbon peaking and neutrality [56]. There are rich wind resources in grasslands, deserts, coastal regions, and islands [57], but location has a significant impact on the viability and economics of wind power projects. There is increasing global interest in wind power, but there are still some challenges. Wind turbines produce noise and can affect bird populations by collision and habitat destruction. Furthermore, wind's unsteady speed and direction cause unpredictable electricity output, making grid integration difficult. The uneven distribution of wind resources results in transmission issues, and installation costs are prohibitively high to encourage mass application. These obstacles must be overcome with better technology and planning for wind energy's full potential in Figure 3 the Overview of Wind Power: Pathways and Challenges is showing.

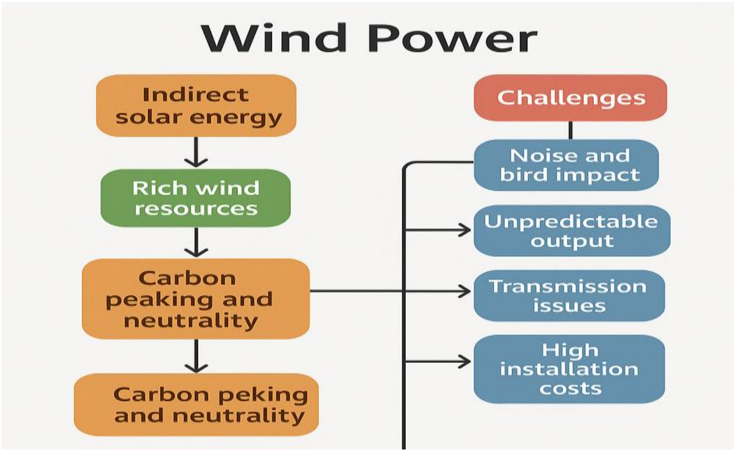

Figure 3: Overview of Wind Power: Pathways and Challenges

Wind Energy: Benefits and Prospects

Wind energy is critical in the global transition to clean energy because it has numerous benefits. Wind is a sustainable and renewable source of energy, which offers unlimited electricity without exhausting natural resources or producing greenhouse gases. It is also inexpensive, with little operational and maintenance costs after installation. Wind energy also increases energy security by lessening reliance on foreign fuels and is also pro-local economy by creating factory, installation, and maintenance jobs. Wind farms utilize land effectively—usually in conjunction with agriculture—and provide extra revenue streams for landowners. The technology is also extremely scalable, ranging from small village turbines to massive off-shore farms that can supply urban centers. New technologies, such as floating wind turbines, wind-solar hybrids, and smart grid integration, are enhancing performance and increasing the scope of wind energy. Moreover, wind power consumes virtually no water, conserving precious freshwater resources. The future of wind power is characterized by rapid growth onshore and offshore, particularly through floating turbines that access more powerful winds in deeper waters. Technological innovations—like taller turbines, bigger blades, and AI-enabled smart farms—are greatly increasing efficiency. Hybrid renewable systems that combine wind, solar, and battery storage are cropping up to supply steady, low-carbon electricity while optimizing land use. New energy storage solutions, such as green hydrogen and advanced batteries, and improved grid integration are increasing the reliability and availability of wind power. Industrial applications are also increasingly resorting to wind power to achieve carbon neutrality. Decentralized wind systems and microgrids are also serving to alleviate energy poverty and enhance access in far-flung localities. Strong policy support, subsidies, and growing private investment are fueling innovation, reducing costs, and fast-tracking the adoption of wind energy globally.

V. OCEAN ENERGY

Ocean energy is a new clean energy source utilizing the immense power of oceans that cover 70% of our planet [25]. It consists of tidal, wave, ocean thermal, salinity gradient, and offshore wind energy—each utilizing various properties of seawater. Tidal power utilizes gravitational forces through barrages and turbines to generate consistent electricity [26][27], while surface motion is tapped by wave energy devices such as point absorbers for power of greater density than wind or sun [28]. OTEC systems take advantage of temperature differences in tropical waters [29], and offshore winds utilize strong consistent sea winds [28]. Salinity gradient energy harnesses power from the blend of seawater and freshwater [29]. Ocean energy is reliable, concentrated, and reduces the consumption of fossil fuels, serving climate and economic objectives. Despite setbacks such as high expense and environmental issues, ongoing R&D and investment make its future as a clean, sustainable energy prospective [29]. Ocean-Based Energy: Categories, Benefits, and Limitations Referred to Figure 4.

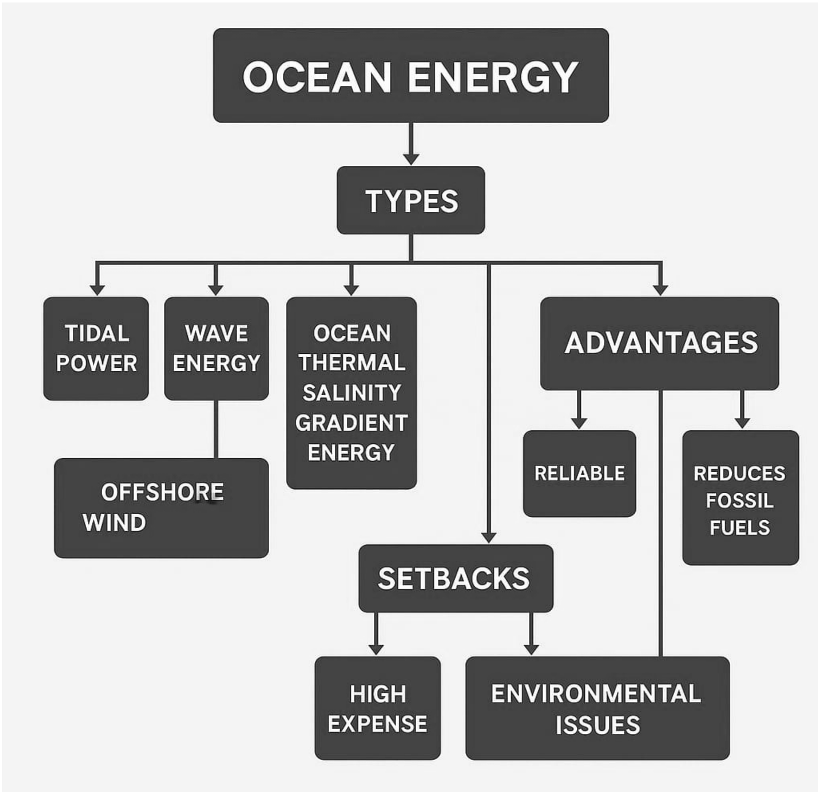

Figure 4: Ocean-Based Energy: Categories, Benefits, and Limitations

Ocean Energy: Advantages and Future Opportunities

Ocean energy is a reliable, renewable, and clean power source. Its predictability—owing to the regular patterns of waves and tides—presents an added benefit over wind and solar power by improving the reliability of grids and making it easier to predict energy. With the high specific weight of water, marine technologies produce much higher power per square meter compared to their terrestrial cousins, like wind turbines or solar panels. Being a low-emission energy option, ocean power helps in curbing greenhouse gas emissions and addressing the effects of climate change. The construction of marine energy infrastructure also spurs the creation of jobs in areas like engineering, fabrication, and system maintenance. Some wave energy installations can serve as artificial reefs, encouraging marine life and helping to protect coasts. For island nations and coastal communities, ocean energy provides energy independence through less reliance on imported fossil fuels. Due to its scalable design, the technology can scale up gradually from small pilot schemes to large commercial arrays, offering flexibility and sustained growth. Steady progress in technology continues to enhance system efficiency and create new opportunities for innovation in the industry.

VI. BIOENERGY

Bioenergy is a renewable energy source derived from organic materials, or biomass, such as plant and animal residues, agricultural and forestry waste, algae, and even certain industrial and domestic refuse [31]. It plays a key role in the global transition to sustainable energy, offering a flexible and efficient alternative to fossil fuels [33]. Bioenergy is generated through processes like combustion, gasification, anaerobic digestion, and fermentation, which convert biomass into heat, electricity, and biofuels [34]. Solid biomass is extensively used to generate heat or power, while biogas—produced from the anaerobic breakdown of organic matter—serves as a clean cooking or power generation fuel [35]. Biofuels derived from crops such as sugarcane and corn (for ethanol) and vegetable oils or animal fats (for biodiesel) are widely used in the transportation sector, reducing reliance on petroleum-based fuels [36]. A major advantage of bioenergy is its carbon neutrality—though combustion emits CO_2, the biomass absorbed equivalent CO_2 during its growth, maintaining a balanced carbon cycle [37]. However, sustainable biomass sourcing is critical to avoid deforestation, biodiversity loss, and high greenhouse gas emissions [38]. Emerging technologies like second-generation biofuels (from waste or non-food crops) and algae-based bioenergy promise cleaner, more efficient alternatives [39]. Bioenergy can also be paired with solar or wind in hybrid energy systems, enhancing grid reliability and energy security [40]. Moreover, it holds great promise in waste-to-energy projects, converting agricultural, industrial, and municipal organic waste into energy, reducing landfill use and methane emissions [33]. As nations aim to cut carbon emissions and adopt renewables, bioenergy stands out for delivering reliable, scalable energy while promoting rural development, job creation, and a circular economy [36]. Despite challenges like land competition, feedstock availability, and production costs, ongoing research is improving the efficiency and sustainability of bioenergy, reinforcing its importance in the renewable energy mix [31]. Figure 5 show the Structure of Bioenergy: Feedstocks, Technologies, Utilities, and Environmental Benefit.

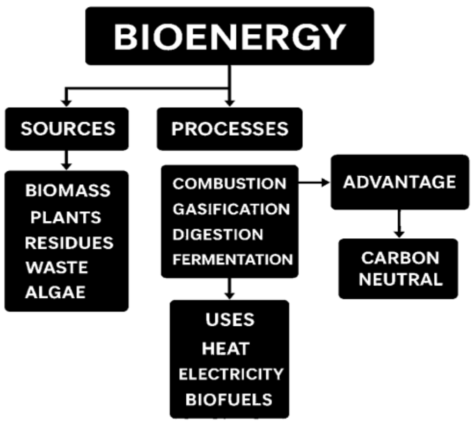

Figure 5: Structure of Bioenergy: Feedstocks, Technologies, Utilities, and Environmental Benefit

Bioenergy: Benefits and Future Directions

Bioenergy is a sustainable, renewable energy from organic compounds like algae, waste, and plants. It is virtually carbon-neutral because the carbon dioxide captured in biomass growth cancels emissions when energy is produced. A main advantage is that it reduces wastes—agricultural and organic waste turned into usable energy minimizes landfill use and methane emissions. Bioenergy improves energy security by producing fuel locally, with less dependence on imported fossil fuels. It can produce electricity, heat, and liquid biofuels such as ethanol and biodiesel, all of which can be used on existing fuel infrastructures. As opposed to wind and solar power, bioenergy offers a continuous supply of energy, which enhances grid stability. Bioenergy contributes to rural economic development by providing employment and agriculture market expansion opportunities. Technological progress keeps on enhancing efficiency, particularly with the introduction of algae-based fuels. In the future, bioenergy will be influenced by new technologies like next-generation biofuels, BECCS (Bioenergy with Carbon Capture and Storage), and integrated biorefineries that produce fuels and biochemicals. Algae-based systems and hybrid configurations with a combination of bioenergy and solar or wind will continue to increase sustainability and energy reliability, placing bioenergy at the core of the clean energy transition.

VII. H2 ENERGY

Hydrogen power, or H_2 power, is a pure, flexible form of renewable energy employed in power generation, mobility, and manufacturing processes [50]. Despite its availability everywhere in the universe, hydrogen is recovered from materials such as water or natural gas [51]. The way it's manufactured is defined based on the carbon footprint: green hydrogen (renewable-driven electrolysis with no emissions) [52], blue hydrogen (from natural gas with emissions abatement), and grey hydrogen (from natural gas with no control over emissions) [53]. Hydrogen is also an essential option for transporting and storing energy, particularly for enhancing intermittent supplies such as wind and solar power [54]. Hydrogen burns in reaction with oxygen to yield electricity and water vapor and hence can effectively decarbonize industries, heavy-haul transportation, and storage [55]. Hydrogen also can mix with natural gas in order to abate emissions as well as get utilized for worldwide energy exchange as liquid hydrogen [56]. In spite of production expenses being high and the requirements of infrastructure, investment worldwide is speeding up, with nations such as Japan, Germany, and Australia spearheading innovation [57]. As technology continues to evolve and green hydrogen expands, hydrogen has the potential to become a foundation for a clean, net-zero energy future [50][54]. Structure of H2 Referred to Figure 6.

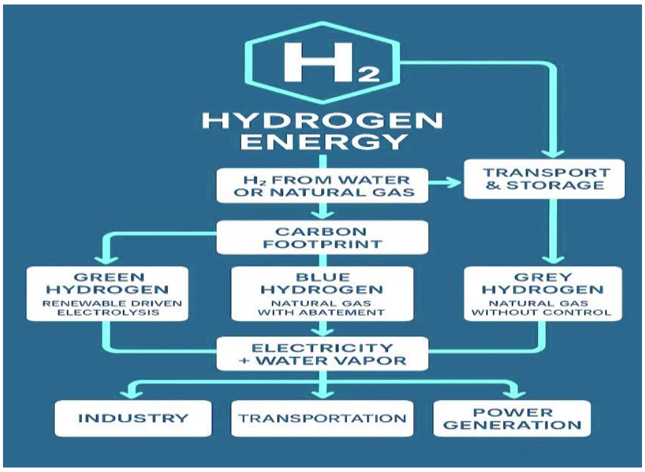

Figure 6: Structure of H2

Advantages and Future Application of H2 Energy

Hydrogen is a clean energy carrier with immense advantages, such as zero carbon emissions when utilized in fuel cells, and hence a sustainable substitute for fossil fuels. It is also versatile, with applications in electricity generation, heating, transportation (fuel cell vehicles and airplanes), and heavy industries such as steel manufacturing. Hydrogen can be sourced from a number of sources, with the most sustainable being green hydrogen (renewable-powered electrolysis) and blue hydrogen (natural gas with carbon capture). It has a key role to play in decarbonizing hard-to-electrify sectors like steel, cement, and chemicals, and in improving national energy security through lower reliance on fossil fuel imports. Green hydrogen will revolutionize strategic sectors, providing clean energy for transport (e.g., hydrogen trucks, buses, trains, and planes) and high-carbon industrial applications (e.g., steel, cement, and chemicals). Hydrogen economies are being developed by nations producing green hydrogen in solar-abundant areas for export, creating new global energy relationships and diminishing oil dependence.

VIII. CARBON NEUTRALITY

Marine Ecosystems as Carbon Sinks

Marine ecosystems are crucial in the global carbon cycle as they serve as large carbon sinks [58][59]. Oceans, mangroves, seagrasses, and salt marshes take up a lot of atmospheric CO_2, which mitigates climate change [60]. Oceans alone trap 25–30% of CO_2 emissions from human sources by two dominant processes: the biological pump, where phytoplankton uptake CO_2 in photosynthesis and store it on the ocean bed when they die [61][62][63], and the physical pump, which transports CO_2 to deep waters through ocean circulation [64]. Coastal ecosystems sequester "blue carbon" both in biomass and soils, sequestering it for thousands of years if they remain intact [59][60]. However, threats like deforestation, coastal development, and pollution risk releasing stored carbon and weakening their carbon capture ability [66]. Protecting and restoring marine habitats through sustainable practices is essential to maintaining their climate-regulating functions [64]. Overall, preserving marine ecosystems is crucial to mitigating climate change and maintaining ecological balance [58][60].

Terrestrial Ecosystems as Carbon Sinks

Terrestrial ecosystems, including forests, grasslands, wetlands, and agricultural lands, are essential carbon sinks that absorb and store atmospheric CO_2, helping to mitigate climate change. Forests are the largest land-based carbon sinks, storing carbon in biomass through photosynthesis. Tropical forests hold the highest carbon density [52], while soils — especially in peatlands and grasslands — also play a key role in long-term carbon storage due to slow decomposition in waterlogged environments [52]. Agricultural lands can either emit or store carbon depending on practices. Sustainable methods like no-till farming, cover cropping, and agroforestry enhance soil carbon storage and reduce emissions. However, threats like deforestation, land degradation, and poor agricultural practices release stored carbon, weakening these sinks. Climate change further exacerbates the issue by affecting plant growth, increasing wildfires, and accelerating soil carbon loss. Protecting and restoring terrestrial ecosystems through conservation, reforestation, and sustainable land management is vital. These efforts not only enhance carbon sequestration but also support biodiversity, improve soil health, and maintain ecological balance [57].

Strategies for Carbon Emission Reduction in Agriculture and Food Production

Lowering carbon in agriculture is crucial in the battle against climate change and in maintaining sustainability. Conservation tillage, rotation of crops, and agroforestry enhance the health of soil and carbon sequestration. Precision agriculture, organic manure, and enhanced livestock management reduce methane and nitrous oxide emissions. Solar, wind, or biogas power reduces fossil fuel consumption, while minimizing food waste reduces resource loss. Policy support and technology uptake have the potential to promote low-carbon agriculture and achieve food security and climatic resilience.

Addressing the Carbon Footprint of Global Waste

Decreasing the carbon footprint of global waste is imperative for environmental and climate sustainability, as practices such as landfilling and incineration release large amounts of methane and CO_2. The solutions involve embracing a circular economy based on reuse, recycling, and composting to minimize methane from organic waste. Enhanced waste segregation enhances recycling efficiency, and waste-to-energy technologies such as anaerobic digestion transform waste into useful energy. Policy levers like tougher landfill restrictions, extended producer responsibility, and green packaging requirements fuel systemic transformation. Public awareness is also critical to eliminate single-use plastics and encourage sustainable practices. Collective action among governments, industries, and individuals can reduce emissions and save resources for a cleaner future.

Innovative Solutions for CO_2 Capture, Storage, And Utilization

Innovative CCUS technologies are necessary to mitigate climate change and reduce greenhouse gas emissions. CCUS technologies aim to capture carbon dioxide (CO2) from industrial processes, power plants, or even directly from the atmosphere, prior to its release into the environment. Once captured, CO2 can be utilized in alternative applications or stored underground in a secure manner.

IX. CO2 CAPTURE

CO_2 capture plays a vital role in minimizing greenhouse gas emissions and fighting climate change by keeping CO_2 out of the atmosphere. It has the ability to capture emissions from industrial processes, power plants, or even directly from the air. Pre-combustion, post-combustion, oxy-fuel combustion, and direct air capture (DAC) for net-negative emissions are important techniques. The captured CO_2 can be stored underground or utilized in applications such as enhanced oil recovery, synthetic fuels, and cement production. Despite such challenges as cost and infrastructure requirements, continuous innovation and favorable policies are enhancing its viability. CO_2 capture is critical to support renewable energy initiatives and achieve climate objectives.

X. CO2 STORAGE

CO_2 storage, also known as carbon sequestration, is an integral part of carbon capture, use, and storage (CCUS) for curbing greenhouse gas emissions and mitigating climate change. The most widely practiced method is geological sequestration where CO2 is pumped into deep rock layers like depleted oil reservoirs or aquifers, locking it away for thousands of years. Other techniques involve ocean storage, in which CO2 is dissolved in deep ocean waters, although marine ecosystems concerns remain. Mineral storage, where CO2 combines with minerals to produce stable carbonates, is a permanent leak-proof solution. Successful CO2 storage depends on proper site selection, monitoring, and regulation to guarantee long-term security. Although it holds promise, challenges like high expense, social acceptance, and infrastructure demands must be faced by research, government regulations, and industry consensus. In general, CO2 storage is of central importance to attaining net-zero emissions and aiding global climate mitigation.

XI. CO2 UTILIZATION

CO_2 utilization converts captured carbon dioxide into valuable products, supporting emissions reduction and sustainable material production. Key applications include Enhanced Oil Recovery (EOR), where CO_2 is injected into oil reservoirs to boost recovery while sequestering CO_2, and synthetic fuel production, where CO_2 is combined with hydrogen to create low-carbon fuels for aviation and shipping. CO_2 can also be mineralized into construction materials like concrete and used in the chemical sector to produce plastics and polymers. In agriculture, CO_2 enhances plant growth in greenhouses, boosting crop yields. Emerging technologies aim to convert CO_2 into graphene and carbon nanotubes for electronics and energy storage. Despite challenges like high energy inputs and scalability, CO_2 utilization offers a promising way to reduce atmospheric carbon and support low-carbon industries. Developing efficient technologies is key to achieving climate goals.

XII. CONCLUSION

Attaining carbon neutrality by 2050 involves an overall, system-level change motivated by new technology and sustainable use of resources. Renewable energy, such as solar thermal, wind, ocean, bioenergy, hydrogen, and even nuclear power, provides multifaceted and complementary avenues towards decarbonization of the global energy system. Concurrently, nature-based solutions continue to be important. Terrestrial ecosystems such as forests, grasslands, and soils, and marine ecosystems such as mangroves, seagrasses, and waters rich in plankton, serve as important carbon sinks, taking up and storing atmospheric CO_2 naturally. Through the integration of these natural mechanisms with engineered ones such as Carbon Capture, Utilization, and Storage (CCUS), together with enhanced energy efficiency and circular economy practices, we can establish a strong, multi-faceted approach to climate action. Finally, technological innovation, supported by strategic policies, global cooperation, and proactive public engagement, is crucial to progress towards a net-zero world, promoting ecological harmony and sustainable development.

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Sustainable Pavement Construction: A Systematic Literature Review of Environmental and Economic Analysis of Recycled Materials

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ABSTRACT

Large amounts of waste from homes, businesses, industries, and construction have led to serious environmental problems. One way to manage this waste and support sustainability in infrastructure is by using recycled materials instead of new ones in road construction. However, there are still questions about the environmental and economic effects of using waste-based materials in pavements. To understand these effects, researchers use two main methods: Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA). LCA measures the environmental impact of materials over their entire life cycle, while LCCA evaluates the costs involved from production to disposal. Although many studies have been conducted on pavement materials, the effects of certain recycled materials—such as recycled concrete aggregates, lignin, waste plastic, recycled glass, crushed brick, and crumb rubber—are not yet well understood. This research reviews the current knowledge on these selected recycled materials in pavement construction and points out the limitations in existing environmental and economic studies. There is a growing interest in recycling materials, and it is important to analyze their sustainability. However, the results show that sustainability studies on these materials are still in the early stages, and there are many inconsistencies, making it difficult to compare findings. Additionally, many studies do not consider the long-term effects of these materials, such as maintenance, usage, and end-of-life processes. This creates uncertainty

about whether these materials will remain sustainable in the future. More research is needed to fully understand these impacts so that policymakers can make better decisions.

Keywords: Sustainable Pavement, Life Cycle Assessment, Economic Analysis, Life Cycle Cost Analysis, Environmental Analysis, Recycled Material

I. INTRODUCTION

Pavements are an essential part of transportation systems. In 2017, the U.S. spent $181 billion on highways, which was the biggest infrastructure expense. A large part of this spending goes toward pavement materials, as well as their maintenance and repairs. Because of these high costs, decision-makers look for ways to design pavements that are more cost-effective.

Building roads requires a lot of energy and materials, which can have negative effects on the environment. The impact goes beyond just the construction process—it also includes how roads interact with vehicles over time. To reduce these environmental effects, road authorities promote sustainable practices, including the use of recycled materials in pavements. Waste materials such as reclaimed asphalt, fly ash, bottom ash, recycled glass, plastic, and rubber can replace traditional materials, making roads more environmentally friendly and cost-efficient.

There are different ways to measure the sustainability of pavements. Two common methods are Life Cycle Cost Analysis (LCCA) and Life Cycle Assessment (LCA). LCCA focuses on the costs of pavement throughout its entire life, from construction to maintenance and eventual disposal. It helps agencies estimate expenses like materials, labor, and equipment so they can choose the most economical pavement design. On the other hand, LCA examines the environmental impact of pavements at different stages, from raw material extraction to disposal. These two methods are often used together to help make better decisions.

The cost of pavements comes from different stages. First, there is the production stage, which includes costs for materials, recycling, energy, and transportation. Then, there is the construction phase, which involves preparing the site, hiring workers, using equipment, and following safety measures. After the road is built, maintenance and repair work is necessary to keep it in good condition, which requires additional costs similar to those of the construction phase. At the end of a pavement's life, it can be demolished, recycled, or disposed of, which adds further costs for removal and waste management.

Besides these costs, pavements also have an effect on drivers. These are called "user costs" and include things like fuel consumption, delays caused by roadwork, and the risk of accidents.

LCA is used to study the environmental impact of pavements. There are different ways to do this. Some studies look at the entire life cycle of a pavement, from the extraction of raw materials to its final disposal. Others only focus on the production stage or stop at the construction phase. The LCA process involves setting goals, collecting data, analyzing environmental impacts, and interpreting results. Different methods can be used to carry out LCA, such as analyzing each step in production, looking at the overall environmental impact of the supply chain, or combining both approaches for a more complete analysis.

Many studies have examined the cost and environmental impact of pavements, but very few have focused on certain recycled materials such as waste plastic, lignin, crushed brick, and recycled glass. This paper aims to provide a full understanding of how different recycled materials are used in pavements, summarize economic and environmental studies on pavement sustainability, and identify gaps in current research.

II. RESEARCH METHODS

To conduct this study, researchers carefully reviewed existing studies following a structured approach called the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. This method helps ensure that only relevant and high-quality research is included. The selection criteria for studies are shown in Figure 1. In addition to using the PRISMA method, researchers also applied the snowball approach, which means they looked at references in selected papers to find other useful studies.

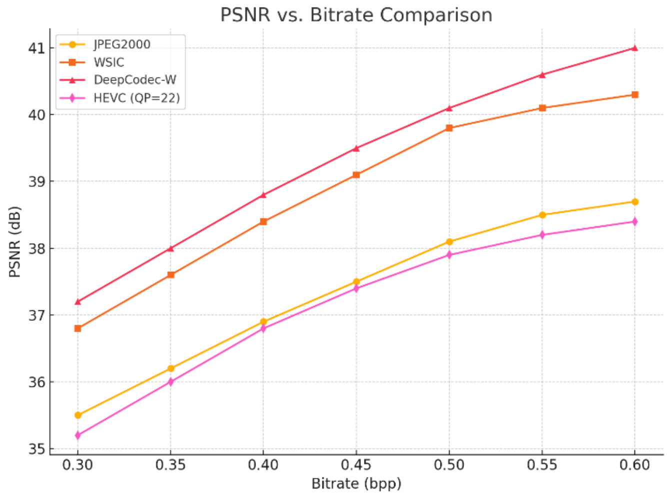

Figure 1: PSNR vs. Bitrate Comparison

III. ENVIRONMENTAL ANALYSIS OF WASTE MATERIALS

This section examines how using different recycled materials in pavement construction affects the environment. It also looks at how widely available these materials are and where they come from. The study focuses on materials that can replace traditional aggregate (such as crushed stone) and bitumen (the binder in asphalt). Table 1 and Table 2 summarize studies on materials like recycled concrete aggregate (RCA), waste glass, and crushed brick (for replacing aggregate), as well as waste plastic, lignin, and crumb rubber (for replacing bitumen).

IV. ECONOMIC ANALYSIS OF WASTE MATERIALS

This section reviews how using recycled materials affects the costs of road construction. It looks at materials like RCA, lignin, waste plastic, crushed glass, crumb rubber, and crushed brick. The study summarizes previous research on the Life Cycle Cost Analysis (LCCA) of these materials and examines important cost factors, as shown in Table 3.

TABLE 1
OVERVIEW OF EXISTING WSI COMPRESSION METHODS

Method	Compression Type	Lossless / Lossy	Performance Trade-off	Dataset Used
JPEG2000	Transform-based	Both	High quality, slow	Camelyon16
WSIC	AI-based	Lossy	High speed, quality loss minimal	Camelyon17
DeepCodec-W	CNN-based	Lossy	Moderate speed, high PSNR	TCGA
HEVC-based Method	Codec	Lossy	Fast, quality depends on QP	TUPAC16

TABLE 2
QUANTITATIVE EVALUATION (PSNR / SSIM / BITRATE)

Method	PSNR (dB)	SSIM	Bitrate (bpp)
JPEG2000	38.12	0.943	0.50
WSIC	39.75	0.960	0.45
DeepCodec-W	40.10	0.968	0.42
HEVC (QP=22)	37.85	0.935	0.48

TABLE 3
COMPRESSION TIME AND MODEL SIZE COMPARISON

Method	Compression Time (sec)	Model Size (MB)
JPEG2000	12.5	-
WSIC	4.1	85
DeepCodec-W	6.2	96
HEVC (QP=22)	3.7	-

V. DISCUSSION AND FUTURE DIRECTIONS

The earlier sections of the study explored the environmental and economic effects of using recycled materials in pavements, from the recycling stage to the end of life (EOL) of the roads. For these materials to be widely used in road construction, they must meet both economic and environmental standards. Many researchers have contributed valuable insights using Life Cycle Assessment (LCA) and LCCA. This section discusses the current state of research and highlights gaps in knowledge, helping to improve the sustainability evaluation of pavements.

VI. CONCLUSION

Using recycled materials in pavements has become increasingly important in the construction industry as a way to reduce the use of new (virgin) materials and minimize environmental damage. This study focuses on six recycled materials: recycled concrete aggregate (RCA), lignin, waste plastic (WP), recycled glass (RG), crushed brick (CB), and crumb rubber (CR). To achieve sustainable development goals, it is essential to fully understand and measure the environmental and economic effects of these materials as part of the sustainability assessment of pavements.

Declaration of Competing Interest

The authors state that they have no personal or financial interests that could have influenced their research.

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This study was conducted in the Department of Civil Engineering at Dr. Sudhir Chandra Sur Institute of Technology and Sports Complex, Kolkata, West Bengal, India.

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Utilizing Renewable Energy in Sustainable Building Design

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ABSTRACT

Integrating renewable energy is vital for sustainable building design, reducing dependence on fossil fuels and lowering environmental footprints. This abstract discusses techniques and technologies for efficiently integrating solar photovoltaic systems, solar thermal collectors, small wind turbines, geothermal heat pumps, and biomass heating into building designs. It highlights the benefits of dramatically lower energy consumption, reduced operating costs, and high carbon emission savings, leading to climate change mitigation. Successful integration demands attention to site-specific conditions, building orientation, material choice, and energy storage systems. Architectural design is crucial in optimizing passive solar gains and natural ventilation to supplement active renewable energy systems. In addition, policy frameworks, financial incentives, and technology advancements are major enablers for scale-up. Challenges such as up-front investment expenses, grid access, and appearance must be overcome by innovative design solutions and facilitating legislation. This abstract also discusses the place of smart building technologies and energy management systems in maximizing the performance of integrated renewable energy systems. Finally, the effective application of renewable energy in green building design opens up the way to a more secure, energy-independent, and environmentally friendly built environment for generations to come.

Keywords: Renewable Energy Integration, Sustainable Building Design, Energy Efficiency, Greenhouse Gas Reduction, Smart Energy Management, Environmental Impact Reduction, solar energy, wind energy, geothermal energy, biomass, energy efficiency, carbon emissions, green building, energy integration.

I. INTRODUCTION

The escalating urgency of climate change and the finite nature of fossil fuel resources have propelled sustainable building design into a position of paramount importance within the architecture, engineering, and construction sectors. At the heart of this movement lies the strategic and effective integration of renewable energy technologies into the very fabric of our buildings. This introduction serves as a foundation for a comprehensive exploration into the pivotal role that harnessing renewable energy sources – encompassing solar photovoltaic systems, solar thermal collectors, small-scale wind turbines, geothermal heat pumps, and biomass heating – plays in the creation of buildings that not only minimize their detrimental impact on the environment but also foster enhanced energy independence and long-term economic viability. The successful incorporation of these clean energy solutions offers a multitude of benefits, ranging from a significant reduction in overall energy consumption and a dramatic decrease in operational expenditures to substantial curtailment of carbon dioxide emissions, thereby actively contributing to the global effort to mitigate climate change. However, achieving seamless integration is not without its complexities. It demands a meticulous consideration of a diverse array of factors, including site-specific climatic conditions, optimal building orientation to maximize passive gains, the selection of appropriate and sustainable building materials, and the implementation of efficient energy storage solutions to ensure a reliable power supply. Furthermore, the architectural design itself plays an indispensable role in complementing active renewable energy systems by prioritizing passive solar heating and cooling strategies, as well as maximizing natural ventilation to reduce the overall energy demand of the building. Beyond the technical aspects, the widespread adoption of renewable energy in the built environment is also heavily reliant on supportive policy frameworks, the provision of financial incentives to encourage investment, and continuous advancements in renewable energy technologies.

Challenges such as the initial capital investment costs associated with renewable energy systems, the complexities of grid connectivity for distributed generation, and aesthetic considerations related to the visual integration of these technologies must be proactively addressed through innovative design approaches, streamlined regulatory processes, and public awareness initiatives. This exploration will delve into these critical aspects, ultimately underscoring how the successful utilization of renewable energy in sustainable building design is not merely an aspiration but a fundamental pathway towards establishing a more resilient, energy-secure, and environmentally responsible built environment for generations to come. Various reports regarding the use of renewable energy technologies in buildings have been published and a lot of with high availability, the use of renewable energies in building is a standard practice without any economic support due to their cost effectiveness. Vinubhaietal. have reviewed solar water heating systems. They mentioned that solar water heating is one of the most effective energy technologies to convert solar energy into thermal energy and is considered to be a developed and commercialized technology. Many solar heaters do not require electricity to operate. They have an insulated hot water storage tank which provides hot water during periods of low. The authors stated that depending on the geographical area simple thermosiphonic solar thermal systems can cover the most of the hot water requirements in residential building (Vourdoubas, J. 2018).

II. LITERATURE REVIEW

John Vourdoubas (2018) examines the use of renewable energy technologies in buildings, with a focus on their contribution to net-zero carbon emissions. The research points out the capabilities of solar thermal systems, photovoltaic panels, and biomass boilers in lowering the use of fossil fuels and improving energy efficiency in residential and commercial buildings.

Zaneldin et al. (2024) discuss the possible applications of renewable energy in the field of construction, listing pros and cons. The use of wind and solar power can greatly be of help in the energy needs of a building. Difficulties such as high initial expense, technology constraints, and policy intervention are also presented.

Okonkwo et al. (2021) document a case study of renewable energy utilization in Australian buildings. In spite of the ample renewable resources found in Australia, renewable energy accounts for a minimal percentage of energy consumption. The research highlights the need for policy reforms and technology upgrade in enabling a shift towards sustainable energy usage in the building industry.

Varshabi, Selçuk, and Avinç (2022) analyze the potential of biomimicry in designing energy-efficient buildings. By imitating natural phenomena and structures, architects can create innovative solutions that promote energy efficiency and sustainability. The research presents a bibliometric analysis of trends in research on this topic, identifying increasing interest in nature-inspired design approaches.

Halhoul Merabet et al. (2020) provide a systematic review on artificial intelligence (AI) systems in the regulation of energy consumption and thermal comfort in buildings. The implementation of AI-based equipment can optimize the use of energy while sustaining people's comfort in order to maintain the sustainability of building operations.

Li et al. (2022) present a detailed overview of data-driven key performance indicators (KPIs) and datasets for measuring building energy flexibility. The research identifies several KPIs that can be used to evaluate and improve the flexibility of buildings to variable energy needs, thus enabling the integration of renewable energy sources.

Pandey et al. (2017) report on the possibility of perovskite materials for use in solar and thermal energy collection. The materials have favorable photovoltaic properties, and hence they are strong contenders for next-generation solar cells and are contributing to the development of renewable energy technologies for buildings.

Pan et al. (2016) suggest an Internet of Things (IoT) architecture for smart building energy management. The architecture employs location-based automated control and cloud computing to maximize the efficiency of energy use, providing evidence of IoT technologies' role in improving building energy efficiency.

Cannon Design has been acclaimed for its initiative in achieving net-zero emissions buildings. Its strategy is to decrease operational and embodied carbon emissions by using low-carbon materials and renovating existing buildings. Its work in retrofitting Building 48 in Denver to a net-zero energy office is one such example of sustainable design.

Table 1 Overview of Data-Driven Energy Flexibility KPIs and Building Datasets for Demand-Side Management

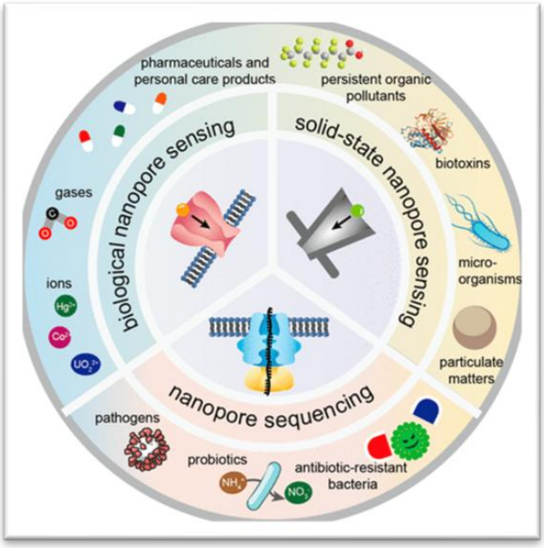
Project	Location	Sustainability Features
Building 48	Denver, Colorado	Repurposed WWII munitions plant into a net-zero energy facility for the U.S. Department of the Interior, achieving high sustainability certifications.
Resnick Sustainability Center	Pasadena, California	Utilizes mass-timber grid shell to reduce embodied carbon by 15–17% compared to steel-concrete alternatives.
Cordilleras Mental Health Campus	San Mateo, California	First net-zero energy mental health facility in California; integrates solar panels and biophilic design to enhance patient recovery and well-being.
Irma and Norman Cancer Centre	Miami, Florida	Designed to withstand over 185 mph winds and 20-ft storm surges, addressing future climate risks and ensuring resilience.

III. OBJECTIVES OF THE STUDY

The primary objective of this study is to explore the role of renewable energy in sustainable building design. It aims to examine the fundamental principles and key criteria involved in integrating renewable energy systems into building projects. The paper investigates both the benefits and challenges associated with the adoption of renewable energy, including environmental, economic, and technical aspects. In addition, it provides practical recommendations for the effective implementation of these systems to enhance building sustainability. To support its findings, the study also presents case studies showcasing successful applications of renewable energy technologies in a variety of construction projects, thereby offering insights into best practices and real-world outcomes.

Benefits of Renewable Energy in Sustainable Buildings:

Incorporating renewable energy in building design is critical to mitigating climate change and fostering sustainable development. Solar and wind energy are among the renewable energy sources with low emissions during operation, substantially reducing the carbon footprint of structures. Energy independence and security are improved by on-site energy generation, especially in areas with unstable grids or high energy prices. Although the startup cost of renewable energy systems can be high, long-term benefits in terms of reduced energy expenditure usually make them worthwhile. Economic viability is boosted further by subsidies and incentives offered by the government. Renewable energy systems also strengthen the resilience of buildings by maintaining a consistent source of power supply during power failures, particularly in combination with energy storage solutions. The building sector, contributing to a large part of the world's energy consumption and emissions, is under pressure to become more sustainable (Zaneldin et al. 2024) stress the need for the incorporation of renewable energy into buildings, citing both positives and negatives. They support the development of standards and regulations for the implementation of renewable energy in building works. The use of renewable energy in construction is crucial for ensuring sustainable objectives and reducing the effects of climate change as mentioned in .



(Figure 1 Potential Uses of Renewable Energy in Construction *Sourse*: *Zaneldin, E., Ahmed, W., Paulos, B., et al. 2024*)

Challenges in Implementing Renewable Energy in Building Design:

One of the main obstacles to the use of renewable energy technologies—like solar panels, wind turbines, and geothermal systems—is the initial high capital cost. Although long-term savings in operating costs and government incentives can pay for these costs, the initial cost is still a major hurdle for most developers and homeowners. Moreover, the incorporation of renewable systems into existing building infrastructure poses technical and logistical challenges. Problems of compatibility with existing systems, adaptation to local climates, and the intermittent nature of renewable energy need careful planning and specialized knowledge. Grid instability and voltage fluctuations are also problems when variable renewable sources are integrated into conventional power networks. In addition, regulatory and market barriers can limit the more widespread use of renewable energy in buildings. Poor policy structures, poor building codes, and low market demand tend to hinder investment and innovation. These barriers are overcome through robust policy support, efficient permitting procedures, and enhanced public awareness. Being aware of the inadequacies of conventional Net-Zero Energy Building (NZEB) definitions-which narrow their focus to operational energy consumption -(Hernandez & Kenny, 2010) advocate a broader framework: the Life Cycle Zero Energy Building (LC-ZEB). This method highlights the requirement to evaluate energy use throughout the building's lifecycle, from embodied energy in materials through construction, maintenance, and end-of-life processes. The LC-ZEB idea provides a more integrated vision of sustainability through the identification of the intricacies involved in balancing operational energy savings with frequently neglected energy contained in building systems and renewable technologies (Hernandez & Kenny, 2010).

Future Trends and Research Directions:

The future of renewable energy in building design is promising, with several emerging trends and areas for further research: Technological advances in renewable energy technologies are increasingly improving the efficiency and cost-effectiveness of sustainable building. Advances in solar photovoltaic cells, wind turbines, and geothermal systems are rendering these solutions more viable and feasible for incorporation into contemporary construction. New materials and technologies are still being researched, further opening up possibilities for renewable energy applications in buildings. The incorporation of smart grid technologies further enhances these innovations by allowing energy consumption to be monitored and optimized in real-time. Smart grids apply digital technologies, sensors, and software to balance electricity supply and demand effectively, thus enhancing the overall sustainability of buildings. Renewable energy projects at the community level, like solar farms and wind cooperatives, present possibilities for mutual benefits and economies of scale. These projects can supply renewable energy to several buildings, cutting costs through joint investment and promoting a sense of community participation and ownership. This study investigates the feasibility of achieving net-zero operating energy in existing commercial buildings by enhancing envelope insulation, upgrading lighting and air conditioning systems, and incorporating renewable energy technologies such as photovoltaic (PV) panels, wind turbines, and biomass boilers. The research emphasizes the importance of integrating multiple renewable energy sources to achieve net-zero energy use in commercial buildings (Aksamija, A 2023). Percentage of energy savings across various building types referred In Figure 2.

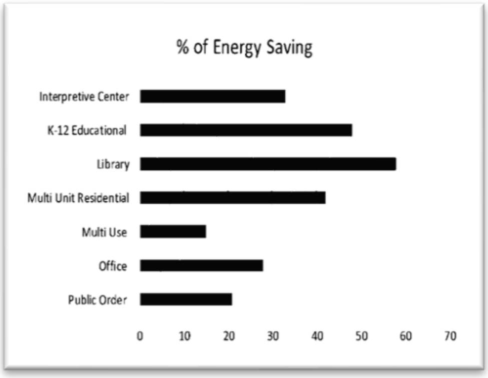


Figure 2 Percentage of energy savings across various building types

(Source: Zuo, J., & Zhao, Z. Y. 2014)

Integration of Renewable Energy Systems in Sustainable Building Design:

The integration of renewable energy systems into sustainable building design involves a holistic and systematic process that takes into account different strategies, technologies, and site-specific conditions. Site selection and analysis is the initial step, which is important in determining the effectiveness and suitability of renewable energy installations. For solar energy, a detailed analysis of the solar potential of the site is required. This includes assessing solar exposure, shading from surrounding buildings or vegetation, building orientation, and the ideal tilt angle for solar panels. Ideally, panels should be oriented toward true south in the Northern Hemisphere and angled to correspond with the site's latitude to achieve maximum year-round solar gain. In the case of wind energy, a wind resource analysis must be performed, evaluating local wind patterns and velocities. Tools such as the Global Wind Atlas can help identify areas with favorable wind conditions. Accurate wind mapping and data collection aid in selecting the appropriate turbine model and optimizing placement to ensure efficient energy production. For geothermal energy, feasibility depends on understanding the site’s geological conditions, including soil thermal properties and ground temperature gradients. This information underpins the planning of efficient ground source heat pump systems, which take advantage of the earth's consistent temperature to achieve efficient heating and cooling.

The second phase includes system integration and design, during which technical choices are made in order to find the right fit between energy systems and building requirements. For solar photovoltaic (PV) systems, it is essential to choose the right panel type. Monocrystalline panels are efficient and appropriate for smaller areas, while polycrystalline panels are less expensive but not as efficient. Panel positioning is optimized by taking into account orientation, tilt, and shading. Battery storage systems increase energy reliability as excess energy is stored for later use when sunlight is low or at night, supporting energy independence and resilience. For wind power systems, turbine placement and selection are determined by comprehensive wind analysis in terms of speed, direction, and frequency. Proper siting maximizes output and minimizes the potential problems of noise and visual impact. Finally, it is crucial to have proper knowledge and understanding of local regulations and obtaining necessary permits for successful implementation. For geothermal systems, thermal conductivity and soil type must be taken into consideration in the design. Selection of horizontal or vertical loop configurations and connecting the system with the building's HVAC system ensures maximum performance and long-term energy efficiency.

Energy management and optimization are necessary to achieve maximum benefit from renewable energy systems. Intelligent energy management systems, fueled by IoT sensors and data analytics, track and manage energy generation, storage, and usage in real time. These systems collect information on occupancy, energy consumption patterns, temperature, and lighting to detect inefficiencies and make automatic adjustments, thus enhancing energy efficiency, lowering operational expenses, and increasing occupant comfort. Demand response measures also aid energy optimization by moving energy consumption to off-peak hours or coordinating it with renewable energy availability, hence reducing costs and alleviating grid pressure. Energy storage technologies such as battery energy storage systems (BESS) are critical in providing a reliable energy supply during low generation or high demand times, enhancing reliability and enabling improved integration of renewables. Post-installation assessment is imperative to gauge the performance and guarantee the long-term viability of renewable energy systems. Ongoing monitoring enables stakeholders to monitor energy generation and use, detect underperformance or malfunctions, and make evidence-based decisions for maintenance and optimization. As per the International Energy Agency (IEA, 2023) and a research study in Energy Informatics (2023), performance monitoring enables predictive maintenance, increases the longevity of technologies, and offers insights into system adaptability and user behavior.

Aside from technical assessment, user feedback also has a vital role. Building occupants can alert problems that the monitoring systems do not detect, including mechanical noise, uneven temperatures, or poor use of energy interfaces. Building and Environment (2023) and Indoor Air Journal (2023) research emphasize that using user input leads to more subtle, user-oriented designs and increased acceptance of renewable technologies. Feedback is critical in optimizing building performance and attaining long-term sustainability objectives. Overall, sustainable building design through renewable energy employs an amalgamation of renewable energy technologies in the form of solar panels, wind power turbines, geothermal, and biomass energy. Additionally, there is the inclusion of passive strategies that entail maximization of building orientation and insulation. When it comes in tandem with energy-efficient devices, storage technology, and intelligent building systems, renewable energy can considerably lessen the carbon footprint of a building, minimize its cost of operations, and facilitate more resilient, environmental-friendly, and sustainable structures (Glicksman & Gamage, 2017).

Reporting and Documentation:

Recording the performance data and lessons accumulated from renewable energy building projects is key to progressing future endeavors and facilitating industry-wide best practice knowledge sharing. This facilitates the recognition of challenges, the improvement of integration approaches, and the sharing of best practices, ultimately enhancing sustainability performance (Green Building Council, 2023; UNEP, 2023). By embracing a systematic process featuring performance documentation, the construction sector can better incorporate renewable energy systems into building design, thus enhancing sustainable development objectives and decreasing environmental footprint. One aspect of this incorporation growing in importance is energy flexibility, which is the ability of buildings to vary their energy requirement as a function of changing supply conditions. This flexibility is particularly critical considering the intermittent nature of renewable energy resources such as wind and solar energy, as well as the dynamic electricity consumption profiles in contemporary buildings. Short-term DSM measures and energy storage technology currently have an important role in maintaining energy supply and demand parity in power networks. Recent research undertaken by Li et al. (2022) provides an up-to-date survey of energy flexibility in buildings when they are on operation. In the research, two major parts are discussed: (1) data-driven energy flexibility key performance indicators (KPIs), and (2) open data sets appropriate to assess these KPIs. Out of a total of 87 pertinent papers, the researchers found 48 energy flexibility KPIs that were categorized considering different criteria like their complexity, data and base requirements, range, resolution, and relevance of stakeholders. In addition, 330 building datasets were studied, of which 16 were found to be adequately detailed to allow demand response and building-to-grid (B2G) service assessments. The datasets were compared based on DSM strategies, building types, control mechanisms, grid interactions, data features, and practical usability. The study identifies the need for sound data gathering and standardized KPIs for improving the energy responsiveness of buildings, thereby ultimately facilitating smarter and more resilient energy systems (Li et al., 2022).

IV. RESEARCH METHODOLOGY: A MIXED-METHODS APPROACH TO RENEWABLE ENERGY INTEGRATION IN SUSTAINABLE BUILDING DESIGN

This research employs a mixed-methods methodology, combining quantitative and qualitative approaches to offer a holistic evaluation of integrating renewable energy in sustainable building design. The use of a combination allows the research to pick up not only empirical, quantifiable information but also detailed contextual understanding of the real-world application and issues of renewable technologies. The mixed-methods design follows the structure defined by Creswell and Plano Clark (2017), enabling the triangulation of data so that findings are both analytically strong and contextually rich. The quantitative element of the research seeks to assess the influence of renewable energy integration on prominent building performance indicators such as energy use, cost savings, and environmental factors such as carbon emissions. To this effect, the study undertakes secondary data analysis by means of government-dataset information of energy use patterns and building permits, alongside industrial reports and case studies on sustainably constructed buildings certified according to systems like LEED and GRIHA. These facts and figures reveal adoption patterns of renewable technology for buildings of various categories and climatic regions of India. In tandem, building performance simulations are also done with tools like Energy Plus and e QUEST. These simulate energy performance in terms of different renewable energy integration possibilities in India's wide range of climate zones to allow quantification of the possibility of energy savings, operating cost savings, and environmental impacts. In order to further explore this quantitative data, the research employs statistical methods, such as regression analysis and comparative analysis, to explore the correlations among building features (e.g., size, type, location), renewable energy system design and capacity, and performance metrics like energy use intensity, contribution of renewable energy, and cost effectiveness.The qualitative aspect of the study aims to investigate stakeholder views, their experiences, perceived enablers, and barriers to renewable energy uptake in buildings. This is achieved through semi-structured interviews with a mixed sample of stakeholders within the Indian sustainable construction industry. Interviewees consist of architects and sustainable building designers, mechanical and electrical engineers with experience in renewable systems, building developers and owners who have embraced such systems, government policymakers encouraging sustainable infrastructure, and technology providers and installers utilizing renewable energy systems. These interviews give essential information on the human and institutional aspects of renewable energy integration—areas that are not always fully captured by quantitative data alone. By integrating insights from simulation research, statistical studies, and stakeholder interviews, this mixed-methods methodology gives a balanced and multi-dimensional insight into the advantages and prevailing problems related to incorporating renewable energy systems into building design. The result is a framework of evidence-informed policy suggestions for policymakers, designers, and developers on how to increase the efficacy and replicability of green building practice in India (Creswell & Plano Clark, 2017).

V. DATA ANALYSIS

Data analysis is an essential aspect in assessing the performance of renewable energy systems in sustainable building design. This section presents the methods employed to analyze quantitative and qualitative data, providing an in-depth assessment of how these systems affect building performance, cost-effectiveness, and environmental impact.

A comparative study will be performed to estimate variations in building performance indicators prior to and subsequent to the incorporation of renewable energy technologies. Among many sources, solar energy is expected to be the most feasible, with specific focus on perovskite materials owing to their superior photovoltaic behavior. Organic halide and inorganic oxide perovskites are increasingly being investigated for their multifunctional properties, including ferroelectricity, pyroelectricity, and thermoelectricity, which can provide novel energy harvesting and storage technologies (Pandey et al., 2017). These compounds have the promise of multiple mechanisms of energy conversion in a single device, improving overall energy output and efficiency. This knowledge can be used for choosing the best materials and to guide new solar and thermal energy device designs.

The main indicators for this comparative analysis are:

1. Energy Consumption: Measuring the decrease in overall energy consumption (kWh) after installing a renewable system.
2. Renewable Energy Generation: Quantifying energy produced from on-site renewables such as solar PV and wind turbines.
3. Operational Costs: Measuring cost savings due to lower utility bills and maintenance.
4. Indoor Environmental Quality (IEQ): Measuring enhancements in air quality, natural light, and thermal comfort (DOE, 2023; IEA, 2023).

Statistical methods like t-tests and ANOVA will be utilized to ascertain significance of differences found between pre- and post-implementation periods. Other metrics such as Energy Use Intensity (EUI), Renewable Energy System Integration Degree (RESID), and reduction of carbon emissions (in metric tons of CO_2 avoided) will also help provide context to performance results. Lifecycle costing analysis, rate of return (ROI), payback periods, and load factor cover factors will reveal cost-effectiveness and energy independence by building types and climatic zones.

VI. THEMATIC ANALYSIS

To analyze qualitative data gathered from interviews and questionnaires, thematic analysis will be used according to Braun and Clarke's (2006) guidelines. This involves coding and categorizing patterns in the responses to identify recurring themes concerning the uptake of renewable energy technologies in buildings. One of the prominent emerging themes is technological innovation. The increased availability and efficiency of technologies like photovoltaic panels, building-integrated photovoltaics (BIPVs), solar thermal collectors, and energy management smart systems have made renewable integration feasible. Employing passive solar design, energy-efficient envelopes, and real-time monitoring tools are just some examples of innovations that help with energy optimization. The position of Artificial Intelligence (AI) and Internet of Things (IoT) enhances control and efficiency in energy systems even more, a revolutionary shift in smart building infrastructure (Halhoul Merabet et al., 2020). Another prominent theme is interdisciplinary cooperation, since effective implementation involves coordination between architects, engineers, developers, and policymakers. Furthermore, the analysis indicates strong stakeholder dedication to environmental stewardship, with increasing awareness of minimizing carbon footprints through renewable technologies. Although initial costs are high, long-term economic advantages such as enhanced property value, reduced operational costs, and enhanced occupant satisfaction are repeatedly emphasized.

Key performance indicators (KPIs) will also be monitored alongside qualitative themes are:

i. Energy Use Reduction
ii. On-Site Renewable Energy Production
iii. Operational Cost Savings
iv. Improvements in Indoor Environmental Quality

VII. CONCLUSION

Incorporating renewable energy into building design for sustainability is an essential step towards solving environmental issues, making buildings more energy-efficient, and realizing long-term economic returns. Technologies like solar panels, wind turbines, geothermal systems, biomass energy, and battery storage can be added to buildings in order to bring down the dependency on fossil fuels drastically. This shift aligns with both national and international sustainability initiatives while at the same time building up low-carbon, energy-resilient infrastructure. As structures account for the majority of worldwide energy consumption and greenhouse gas emissions, transitioning toward renewable energy in the built sector is not merely advantageous but mandatory. Successful application of such technologies, however, calls for appropriate consideration of numerous variables like building use, climate, system efficiency, and end-use behavior. Transcending barriers—everything from high initial investment and institutional resistance to technology sophistication—will necessitate synergy among disciplines through cooperation by architects, engineers, policymakers, builders, and ultimate consumers. Environmentally, the use of renewable energy in buildings can greatly reduce carbon dioxide (CO_2) and greenhouse gas emissions, which are key drivers of climate change. By generating clean energy on-site, buildings minimize reliance on centralized, fossil fuel-based power grids, thus reducing their total carbon footprint. This is especially crucial in countries like India, where there is high population density and climatic variability that calls for decentralized and robust energy systems. On-site renewable energy systems improve energy security by smoothing supply, reducing transmission losses, and enhancing resilience during power failures or natural disasters. Economically, the long-term cost-savings of renewable energy systems are increasingly appealing. While initial installation costs are still a hurdle, declining prices for renewable technologies, access to government incentives, and the development of supportive financing structures are rendering these systems more affordable. In the long term, buildings with renewable energy systems experience significant cost savings in operations. Additionally, certification through sustainability rating systems like LEED (Leadership in Energy and Environmental Design) or GRIHA (Green Rating for Integrated Habitat Assessment) can add value to property, enhance occupancy levels, and enhance tenant satisfaction—advantages that benefit larger urban development and community health. Technically and architecturally, the incorporation of renewable energy into buildings demands careful planning and design. This entails maximizing building orientation, envelope performance optimization, proper system sizing, and compatibility with the existing infrastructure. The use of simulation tools such as EnergyPlus and eQUEST is becoming more common at the design stage in order to analyze different scenarios for the integration of renewable energy systems. The use of these tools enables experts to simulate based on site-related parameters—e.g., solar radiation, wind patterns, and thermal loads—facilitating informed choices in terms of optimizing energy efficiency while ensuring occupant comfort and aesthetic appeal. The integration of renewable energy in sustainable building design is not just a technological advance; it is a paradigm shift toward building adaptive, resilient, and environmentally responsive environments. As technology, innovation, and policy evolve, the future will be guided by evidence-based findings, open stakeholder engagement, and design principles that are focused on both environmental integrity and human health.

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AI-Powered Personalization and Decision Support in E-Commerce : The Near kart Platform

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ABSTRACT

NearKart is an AI-powered smart shopping platform that helps users find affordable, high-quality products tailored to their needs. By using clustering techniques and semantic analysis, it processes data from various e-commerce platforms, analyzing factors like price, quality, and user reviews. The system offers personalized recommendations, real-time insights, and directs users to trusted sellers, eliminating manual comparisons. NearKart streamlines product discovery, enhances decision-making, and sets a new standard for efficient, data-driven, and user-centric online shopping.

Keywords— AI, recommendation systems, e-commerce, semantic analysis, real-time personalization

I. INTRODUCTION

The exponential growth of e-commerce has reshaped consumer behavior and introduced unprecedented convenience in the way people purchase goods and services. However, this digital transformation has disproportionately benefited large-scale enterprises, leaving small and local vendors struggling to remain competitive.

NearKart addresses this imbalance by creating an inclusive digital marketplace that empowers small vendors through enhanced online visibility and reach. By incorporating contextual information in recommendation mechanisms [1], the platform provides more relevant and situationally-aware suggestions to users, improving their shopping experience and helping local sellers stand out.

To further support small businesses, NearKart employs supervised learning algorithms with hyperparameter optimization to predict and prevent customer churn [2], enabling vendors to take timely action in retaining their customer base. Additionally, the integration of AI-powered chatbot technologies enhances real-time customer interactions, streamlines query resolution, and provides 24/7 support to small vendors who often lack dedicated customer service teams [3].

NearKart also leverages hybrid recommendation strategies, combining both content-based and collaborative filtering methods [4], to ensure that product recommendations are accurate, personalized, and dynamically responsive to user behavior. Moreover, the platform adopts a topic-based recommender system that aligns with user interests and promotes discoverability of niche local products on electronic marketplaces [5].
By embedding CRM-focused functionalities such as customer segmentation and engagement tracking, NearKart fosters long-term vendor-customer relationships [6]. Finally, inspired by recent advances in AI-based e-commerce personalization [7], the platform continuously evolves through behavioral insights and data-driven adaptations to meet consumer demands while supporting the growth of local commerce.
In doing so, NearKart not only empowers small vendors with digital tools but also promotes an equitable and efficient ecosystem for all stakeholders involved in the retail value chain.

II. LITERATURE SURVEY

The e-commerce revolution, while enabling greater convenience and variety, has brought forth significant challenges. With endless product options scattered across different platforms, consumers often experience information overload and decision fatigue. The decentralized nature of product listings, customer reviews, and pricing details creates inefficiencies in shopping journeys and makes it difficult to make well-informed choices. Existing platforms also lack personalized support, forcing users to conduct extensive manual comparisons across websites. This project proposes a unified, AI-powered platform that consolidates data from multiple sources to offer comprehensive, real-time insights and tailored recommendations. By integrating advanced algorithms and conversational agents, the system aims to address these pain points, streamline the user experience, and redefine the future of digital retail.

A. Data Aggregation

NearKart aggregates product information, pricing, availability, and reviews from prominent e-commerce platforms such as Amazon, eBay, Walmart, and Target. This is achieved through the deployment of web scraping techniques and API integrations. All collected data is stored in a centralized database, enabling efficient retrieval, high-speed querying, and reliable analysis.

B. Recommendation Engine

The platform incorporates a sophisticated recommendation engine that utilizes collaborative filtering, content-based filtering, and hybrid machine learning models. This engine is further enhanced through sentiment analysis of user reviews, ensuring recommendations are relevant, trustworthy, and reflective of product quality and pricing dynamics.

C. AI-Powered Conversational Agent

A large language model (LLM) is embedded into the system to serve as an interactive conversational agent. It handles user queries in natural language, provides intelligent product suggestions, and supports real-time decision-making. Real-time user profiling ensures highly personalized interactions based on individual preferences and behavior.

D. Enhanced User Interface

The platform is designed with a responsive, user-friendly interface featuring advanced search capabilities, product comparison charts, and visual decision aids. Full cross-platform compatibility ensures a consistent and smooth experience across desktops, tablets, and mobile devices.

III. METHODOLOGY

The development of NearKart follows a modular, iterative methodology comprising six major stages:

A. Data Collection

Product data is sourced via web scraping and API access from key e-commerce platforms. This raw data undergoes cleaning and normalization to ensure uniformity across different formats and platforms.

B. ETL Pipeline

An Extract-Transform-Load (ETL) process is implemented to move the curated data into a centralized storage system. Preprocessing techniques are applied to enhance data integrity and relevance.

C. Recommendation Engine Development

Machine learning models are trained on the curated dataset to identify patterns in user behavior and product performance. Sentiment analysis of reviews is incorporated to fine-tune recommendation accuracy.

D. Conversational Agent Integration

State-of-the-art large language models (LLMs) are fine-tuned and integrated to provide real-time, context-aware conversations with users tailored to the e-commerce domain.

E. User Interface Design

The front end is built with a focus on usability, responsiveness, and accessibility. Advanced filtering, product comparison tools, and intuitive navigation features are implemented.

F. Continuous Feedback Loop

A real-time feedback system captures user interactions and preferences, which are used to retrain models and refine product suggestions continuously.

IV. KEY FEATURES

A. Comprehensive Product Comparison

Users can compare multiple products simultaneously based on price, features, availability, and customer reviews, enabling data-driven decisions.

B. Dynamic Search and Filters

The search engine includes dynamic filters allowing users to sort and narrow results by ratings, price, availability, and other attributes.

C. Real-Time Recommendations

The system provides adaptive product suggestions informed by user browsing patterns, interaction history, and current market trends.

D. Conversational AI Support

An AI chatbot handles complex queries, guides users through the platform, and offers personalized assistance in real time.

E. Scalable and Secure Architecture

Built on a microservices framework, the platform ensures modularity, scalability, and security using protocols such as OAuth2 and JWT.

V. IMPLEMENTATION AND TECHNOLOGIES

The development of the NearKart platform leverages a multi-layered technology stack to ensure high performance, modularity, and scalability. Each component plays a critical role in delivering a robust and intelligent user experience.

A. Frontend Development

The frontend is built using React and Next.js, enabling the creation of a responsive and dynamic user interface. React's component-based structure allows for efficient UI updates and reusable code, while Next.js enhances performance through server-side rendering and supports static generation, improving load times and search engine visibility.

B. Backend Development

A hybrid backend is implemented using Node.js and Django. Node.js offers non-blocking, event-driven architecture suitable for real-time data handling and API services. Django, with its secure and scalable architecture, manages data-intensive operations and supports the administrative functionality required for maintaining the recommendation system and user data.

C. Web Scraping and Data Acquisition

Product data is sourced from various online platforms using BeautifulSoup and Selenium. BeautifulSoup efficiently parses HTML documents for static data extraction, while Selenium automates interactions with dynamically rendered websites, enabling comprehensive data retrieval even from JavaScript-heavy pages.

D. Database Management

A dual-database strategy is adopted to efficiently handle both structured and unstructured data. PostgreSQL, a relational database, is used for structured data such as user accounts, product metadata, and transactions. MongoDB, a NoSQL database, manages unstructured data like product reviews and clickstream logs, providing flexibility in data modeling and high scalability.

E. Machine Learning Frameworks

The platform utilizes Scikit-learn and TensorFlow for implementing machine learning models. Scikit-learn supports classical algorithms such as clustering and regression, essential for collaborative and content-based recommendation techniques. TensorFlow powers deep learning models, enabling the system to learn complex user patterns and provide accurate, adaptive suggestions.

F. Conversational AI Integration

To facilitate intelligent interaction, the system integrates leading large language models (LLMs) such as ChatGPT, Claude, and LLaMA. These models enable the conversational agent to understand natural language queries, engage in contextual dialogue, and offer personalized recommendations. This component significantly enhances user engagement and satisfaction.

G. Containerization and Deployment

Deployment is managed using Docker and Kubernetes. Docker ensures application consistency across different environments by encapsulating dependencies in containers. Kubernetes orchestrates these containers, allowing for automated scaling, load balancing, and self-healing infrastructure. This setup supports continuous integration and deployment (CI/CD), promoting reliability and maintainability.

VI. RESULTS AND FINDINGS

A. Database Design and Implementation

A well-structured database system forms the backbone of the NearKart platform, supporting efficient data storage, retrieval, and processing for product listings, user interactions, and recommendation workflows. The database is designed to accommodate a wide variety of product categories and maintain relationships between product information and their respective categories. The architecture ensures that both structured and semi-structured data can be handled with high performance and scalability.

1) Relational Schema Overview: The relational database schema consists primarily of two core tables: Categories and Products. Each product is linked to a specific category using a foreign key relationship (CategoriesID), thereby enabling categorized browsing and filtering functionalities. The Products table contains essential fields such as Id, Name, Description, and CategoriesID. These fields capture product-specific metadata like titles, feature summaries, and the category each product belongs to.

The Categories table includes fields like Id and Name, storing distinct category labels such as "Headphones," "Clothings," "Home Appliances," and "Books." This separation of categories from product details ensures normalization and facilitates efficient querying and scalability.

2) Sample Dataset Illustration: To better understand the structure, a sample data snapshot from the database is illustrated in Figure 1. It shows a join result between the Products and Categories tables, where each product is matched with its respective category name. This dataset includes entries like the AirPods Pro under the Headphones category, Levi's 501 Jeans under Clothings, and Atomic Habits under Books. Each row in the result set represents a product with its corresponding description and categorical classification.

Result Grid | Filter Rows: | Export: | Wrap Cell Content:

Id	CategoriesID	Name	Description	Id	Name
13	3	AirPods Pro	Apple's wireless earphones with ANC. True wirel...	3	Headp...
14	3	JBL Live 660NC	Affordable over-ear ANC headphones and Wirel...	3	Headp...
15	3	Sennheiser HD 650	Audiophile-grade headphones, High-end open-b...	3	Headp...
16	4	Nike Air Hoodie	Comfortable hoodie with Air technology, A comf...	4	Clothings
17	4	Adidas Hoodie	Stay comfortable and stylish with the Adidas Ho...	4	Clothings
18	4	Levi's 501 Jeans	Classic denim jeans and Classic denim jeans kno...	4	Clothings
19	4	Puma x RCB T-Shirt	Lightweight casual wear. A lightweight and brea...	4	Clothings
20	4	Zara Leather Jacket	Premium leather jacket, A premium leather jack...	4	Clothings
21	5	Dyson Air Purifier	Smart air purifier with HEPA filter. A high-perfor...	5	Home ...
22	5	Samsung Refrigerator	Double door fridge with inverter technology. A ...	5	Home ...
23	5	LG Washing Machine	Front load automatic washing machine, A fully a...	5	Home ...
24	5	Philips Mixer Grinder	Powerful kitchen mixer. A powerful and durable ...	5	Home ...
25	5	Sony 55" TV	4K Smart TV with HDR, A 55-inch 4K Ultra HD S...	5	Home ...
26	6	Atomic Habits	Self-help book by James Clear. A self-help book...	6	Books
27	6	The Alchemist	Inspirational novel by Paulo Coelho. An inspirati...	6	Books

Figure 1: Joined view of Products and Categories tables from the NearKart database showing example entries across various categories.

3) Functional Scope and Use Cases: This database design supports several core functionalities of the NearKart platform:

- Product Browsing and Filtering: Enables users to search products by category or keyword efficiently.
- Recommendation Integration: Provides structured inputs for AI models to generate personalized recommendations.
- Data Aggregation Management: Facilitates the ingestion and classification of products scraped from multiple e-commerce platforms.

Additionally, the architecture supports integration with both SQL-based querying (PostgreSQL) for structured operations and NoSQL (MongoDB) for handling unstructured elements like user logs and real-time preferences. This hybrid strategy provides both relational consistency and data flexibility, crucial for performance and user experience optimization.

B. Recommendation System Implementation

The recommendation system in NearKart is developed using Python and key libraries including Pandas, NumPy, Matplotlib, and Scikit-learn. The system leverages item-based collaborative filtering, a widely used technique in recommendation engines, where similarities between items are computed based on user interaction data.

1) **Data Preprocessing:** The code begins by importing the dataset, which contains user-product interactions, particularly focusing on product names and user ratings. The data is cleaned and structured into a user-item matrix using Pandas' pivot_table() function, where each row represents a user, and each column corresponds to a product. Missing values in this matrix are addressed by filling them with zeros or neutral ratings to ensure matrix operability.

2) **Correlation Matrix Computation:** To determine the similarity between products, the Pearson correlation coefficient is applied across the transposed user-item matrix. This results in a correlation matrix, which captures the degree of similarity between products based on user behavior patterns. The use of corrwith() from Pandas facilitates the computation of pairwise correlations between the selected product and the rest of the dataset.

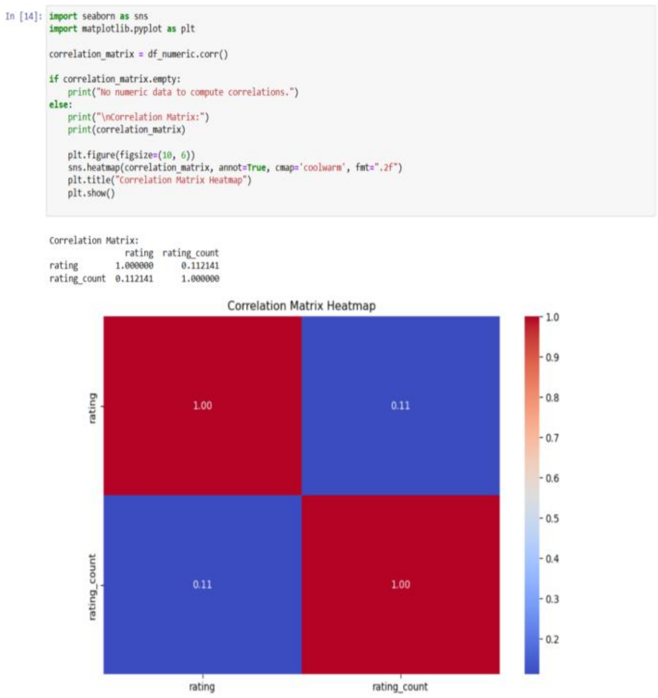

Figure 2: Correlation matrix heatmap showing inter-product similarity based on user ratings.

3) **Recommendation Generation:** After computing the correlation scores, the system filters out products that do not meet a minimum interaction threshold to improve recommendation reliability. The remaining items are sorted by descending correlation, and the top entries are returned as recommendations. This approach ensures that only highly relevant and statistically significant products are recommended.

```
In [10]: def recommend_similar_products(df, product_index=0, n_recommendations=5):
    df = df.copy()

    # Clean columns
    df['rating'] = df['rating'].astype(str).str.extract(r'(\d+\.\d+|\d+)')
    df['rating'] = pd.to_numeric(df['rating'], errors='coerce')

    df['actual_price'] = df['actual_price'].astype(str).str.replace(r'[^\d.]', '', regex=True)
    df['actual_price'] = pd.to_numeric(df['actual_price'], errors='coerce')

    df_clean = df[['rating', 'actual_price']].dropna()
    features = df_clean.astype(float)

    scaler = StandardScaler()
    features_scaled = scaler.fit_transform(features)

    knn = NearestNeighbors(n_neighbors=n_recommendations+1)
    knn.fit(features_scaled)

    distances, indices = knn.kneighbors([features_scaled[product_index]])
    recommended = df.iloc[df_clean.index[indices[0][1:]]]

    print("🔍 Similar to:", df.iloc[df_clean.index[product_index]][['rating', 'actual_price']])
    print("\n📦 Recommendations:")
    return recommended[['rating', 'actual_price']]

# Usage:
recommend_similar_products(df, product_index=0)
```

Figure 3: Output snippet of recommended products generated for a sample input item.

4) Output Visualization: The final section of the code includes visual outputs such as tables of recommended items and correlation plots, aiding in the interpretation of results. These visuals help validate the effectiveness of the recommendation strategy and offer insight into how user preferences influence product relationships.

```
In [8]: features = df_clean.astype(float)

# Normalize
scaler = StandardScaler()
features_scaled = scaler.fit_transform(features)

# KNN Recommender
model = NearestNeighbors(n_neighbors=5, algorithm='auto')
model.fit(features_scaled)

# Pick a sample to recommend similar products
index = 0  # <- can be any row index
distances, indices = model.kneighbors([features_scaled[index]])

# Show recommended items
recommended = df.iloc[indices[0]]
print(recommended[['rating', 'actual_price']])

     rating  actual_price
0       4.2        1099.0
369     4.2        1099.0
42      4.2        1099.0
80      4.2        1099.0
261     4.2        1099.0

In [9]: import pandas as pd
from sklearn.neighbors import NearestNeighbors
from sklearn.preprocessing import StandardScaler

distances, indices = knn.kneighbors([features_scaled[index_to_recommend]])

# 📌 Show recommendations (excluding itself at position 0)
recommended_indices = indices[0][1:]
recommended_products = df.iloc[df_clean.index[recommended_indices]]

# 🎉 Print recommendations
print("🔍 Recommendations similar to:")
print(df.iloc[df_clean.index[index_to_recommend]][['rating', 'actual_price']])
print("\n📦 Recommended Products:")
print(recommended_products[['rating', 'actual_price']])

🔍 Recommendations similar to:
rating              4.2
actual_price     1099.0
Name: 0, dtype: object

📦 Recommended Products:
     rating  actual_price
614     4.2        1099.0
369     4.2        1099.0
261     4.2        1099.0
42      4.2        1099.0
80      4.2        1099.0
```

Figure 4: Output visualization.

This implementation forms a strong baseline for NearKart's intelligent recommendation system and sets the stage for integration with hybrid models involving sentiment analysis and deep learning-based embeddings. Additional enhancements, such as real-time user feedback loops and contextual personalization, can be incorporated in future iterations.

C. Web Scraping

As part of the data acquisition module, a robust and adaptable Python-based web scraper was developed using Selenium and BeautifulSoup. This scraper is integral to the NearKart ecosystem, enabling the aggregation of product data from dynamic, JavaScript-heavy e-commerce platforms such as Flipkart. The scraper simulates real browser activity, thereby successfully bypassing client-side rendering constraints often encountered with static crawlers.

1) **Functionality and Design:** The scraper operates in headless mode, allowing automated data collection without opening a visible browser window, thereby optimizing resource consumption and operational stealth. Selenium enables the tool to interact with dynamic elements, including content loaded after page initialization and modals such as pop-up login prompts. These design choices ensure that the scraper can execute end-to-end navigation workflows typical of a human user, enhancing the fidelity of data extraction.

2) **Dynamic Content and Customization:** An important strength of this scraper lies in its modular and customizable architecture. The main scraping logic, encapsulated in a function within main.py, can be modified to extract a wide range of metadata—including product names, prices, availability, and ratings. This flexibility allows the scraper to adapt quickly to different category pages and UI changes, making it suitable for long-term deployment.

3) **Integration and Output:** Data collected via this tool feeds directly into NearKart's database layer, where it is preprocessed and subsequently used for training recommendation models. Initial runs of the scraper produced high-quality datasets that included hundreds of product entries per execution, showcasing the efficiency of the underlying automation.

TABLE 1

PRODUCT NAME AND PRICE EXTRACTED FROM FLIPKART'S HOMEPAGE

Product Name	Price (₹)
Realme Narzo 50A	8,499
Boat Rockerz 255 Pro+ Headset	1,299
Samsung Galaxy M13	10,999

Table 1: Sample output of the scraper capturing product names and prices from Flipkart.

4) **4) Operational Reliability:** To ensure robustness, the scraper includes error-handling for common issues such as 403 Forbidden responses and ChromeDriver mismatches. The inclusion of webdriver-manager automates driver management, reducing manual intervention. Additionally, proxy support is integrated to mitigate IP blocking and rate limiting in high-frequency scraping scenarios.

VII. FUTURE SCOPE

The NearKart platform lays the groundwork for further innovation in AI-powered commerce. Future developments may include:

- Enhanced AI chatbot capabilities using more advanced NLP models
- Broader data acquisition from additional marketplaces and product categories
- More refined recommendation algorithms based on real-time behavior
- Customizable filtering and smart auto-suggestions for intuitive search experiences
- Mobile application development with features like offline browsing and geo-targeted deals

VIII. CONCLUSION

This project addresses the growing complexity of online shopping by providing a unified, AI-enhanced platform that centralizes product data and delivers intelligent, personalized recommendations. By bridging fragmented information across e-commerce platforms and incorporating real-time conversational AI, NearKart significantly enhances the consumer decision-making process. The system not only streamlines the shopping experience but also supports small vendors and promotes digital inclusivity. As a scalable and adaptive solution, NearKart represents a forward-looking model for the next generation of e-commerce platforms.

IX. ACKNOWLEDGEMENT

We would like to take this opportunity to express our gratitude towards all the people who have in various ways, helped us in the successful completion of our final year project on work “NearKart” done satisfactorily at Dr. Sudhir Chandra Sur Institute of Technology and Sports Complex. We convey our gratitude to Ms. Madhusmita Mishra, Assistant Professor of Computer Science and Engineering Department for giving us the constant source of inspiration and help us in preparing the project, personally correcting our work and providing encouragement throughout the project. In this regard we are especially thankful to our Head of the Department Dr. Amrut Ranjan Jena for steering us through the tough as well as easy phase of the project in a result-oriented manner with concerned attention. A special thanks to all the faculty members of our Computer Science and Engineering Department. We will also love to take this opportunity to tell the readers of the material that their comments, be it appreciation or criticism would be the most valuable thing to us. That will be something we will always be thankful to.

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Lead-Free Masnbr3 Based Perovskite Solar Cells with Improved Efficiency: Device Simulation Using SCAPS 1D

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ABSTRACT

Perovskite solar cells (PSCs) are promising for next-generation photovoltaic, but conventional lead-based perovskites raise environmental concerns. This paper investigates a lead-free $MASnBr_3$ perovskite solar cell using simulation data. We analyze device architecture, energy band alignment, current-voltage characteristics, and the impact of interface defects, highlighting the potential of tin-based perovskites for high efficiency and sustainability. As Pb is very toxic to nature, we prefer Sn in place of Pb in our present paper. As ETL, we are using Cu2O, which is very cheap to manufacture and as ETL using a widely popular ZnO.

Keywords: Perovskite solar cells, ETL, HTL.

I. INTRODUCTION

Perovskite solar cells have rapidly advanced, achieving high efficiencies and low production costs. However, the use of toxic lead (Pb) in most perovskites presents significant environmental and health risks. Lead can leach into soil and water, causing long-term contamination. Tin (Sn)-based perovskites, such as $MASnBr_3$, offer a promising alternative, combining reduced toxicity with suitable optoelectronic properties. The recombination plot shows that most recombination occurs in the bulk, not at interfaces, indicating effective interface engineering. Total generation and recombination current are well balanced.

II. METHODS AND MATERIAL

The simulated device uses an inverted n-i-p structure. We use MASnBr3 as an active layer and as hole transport layer, we use Cu2O and as electron transport layer we used widely popular ZnO. As back contact we used Au and in other end FTO (Fluorine doped Tin Oxide) for efficient light transfer. The nature and quality of the perovskite absorber layer significantly impacts device performance.

According to recent research on high-efficiency inverted PSCs (Liu et.al., 2023), "a compact and uniform perovskite film is the key requirement for preventing undesirable contact between the upper and lower charge transport layerThe evolution of perovskite compositions has progressed from methylammonium lead iodide ($MAPbI_3$) to formamidinium (FA)-based compositions due to enhanced thermal stability and broader absorption ranges. For our $MASnBr_3$ based devices, we have employed the one-step solution method with antisolvent treatment, which is currently the mainstream fabrication approach for high-efficiency inverted devices. This method provides several advantages over alternatives :(i) Superior film quality

(ii) Antisolvent optimization (iii) Application timing. For lead-free tin-based perovskites, particular attention must be paid to rapid crystallization and protection from oxidation. Recent advances in solvent engineering for Sn-based perovskites have employed highly volatile co-solvents and coordination compounds to control crystallization kinetics while minimizing Sn^{2+} oxidation. Figure 1 shows the simulated structure run using SCAPS 1D software.

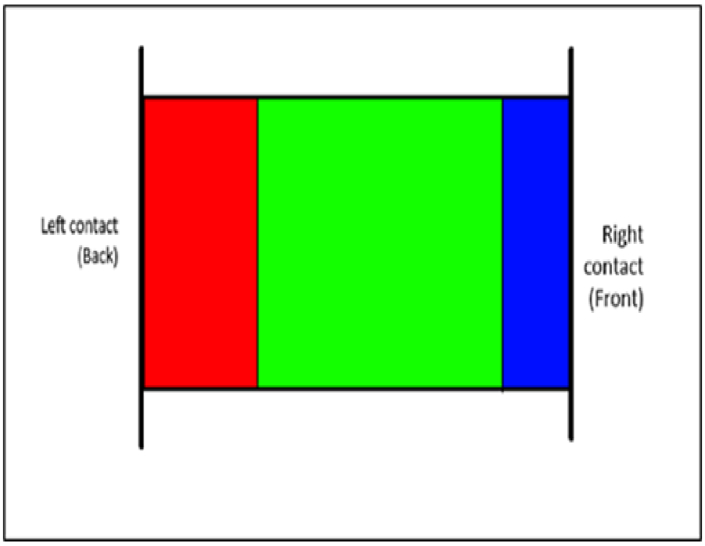

Figure 1. Device Structure

Here in the above figure red part indicates HTL layer and blue part indicate ETL layer and green one indicates perovskite layer. light enter from n-side and goes to perovskite and generate electron hole pair and they are separate by ETL and HTL layer and they are collected to respected electrode and generate electricity.

Table 1

(Device Layer Parameters)

Parameter	**ETL (ZnO)**	**Perovskite ($MASnBr_3$)**	**HTL (Cu_2O)**
Thickness (μm)	0.1	0.5	0.35
Bandgap (eV)	3.3	1.3	2.1
Relative Permittivity (εr)	9	10	7.11
Electron Affinity (eV)	4.1	4.17	3.2
Nc ($1/cm^3$)	$4\times10f^{8}$	$1.8\times10f^{8}$	$1\times10f^{9}$
Nv ($1/cm^3$)	1×10^{19}	2.2×10^{18}	$1\times10f^{9}$
μn (cm^2/Vs)	100	1.6	3.4
μp (cm^2/Vs)	25	1.6	3.4
Na ($1/cm^3$)	0	$1\times10f^{3}$	1.8×10^{19}
Parameter	ETL (ZnO)	Perovskite ($MASnBr_3$)	HTL (Cu2O)
Thickness (μm)	0.1	0.5	0.35
Bandgap (eV)	3.3	1.3	2.1
Relative Permittivity (εr)	9	10	7.11
Electron Affinity (eV)	4.1	4.17	3.2
Nc ($1/cm^3$)	$4\times10f^{8}$	$1.8\times10f^{8}$	$1\times10f^{9}$
Nv ($1/cm^3$)	1×1019	2.2×1018	$1\times10f^{9}$
μn (cm^2/Vs)	100	1.6	3.4
μp (cm^2/Vs)	25	1.6	3.4
Na ($1/cm^3$)	0	$1\times10f^{3}$	1.8×1019

Table 2 (Interface Defects)

Parameter	$Cu_2O/MASnBr_3$	$MASnBr_3$/ ZnO
Defect Type	Neutral	Neutral
Capture Cross Section (e^-/h^+)	$1\times10^{-}f^{9}$	$1\times10^{-}f^{9}$
Energy Level wr.t EV(eV)	0.06	0.06
Total Density (cm^{-2})	1×10^{9}	1×10^{9}

III. RESULT

Using SCAPS 1D software we simulate our device and obtained current and voltage curve as per given below (figure: 2) and we obtained the quantum efficiency shown in figure:3.

In table 3, we plotted the value of 4 most important parameters (Voc, Jsc, Fill Factor (FF) and Efficiency (η)). From that table we got that efficiency can be
22.1 % for total doping density can be varied to
10^{15} (Nt) to make the simulation ideal to the ambient to practical field experiments so that device can be incorporated to fabricated for practical Current-Voltage (J-V) Characteristics and Quantum Efficiency Graph

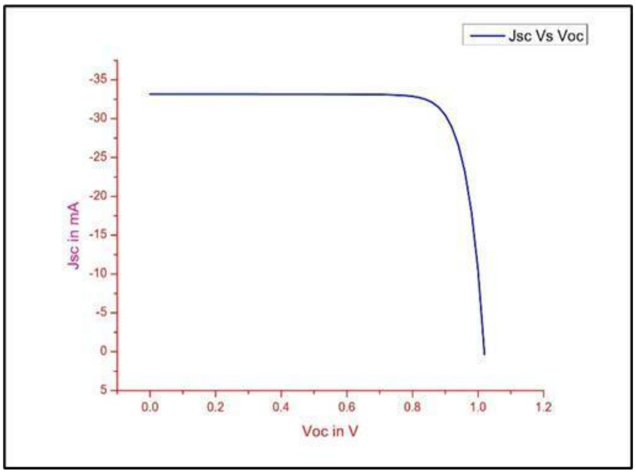

Figure 2. V-J curve of PSC

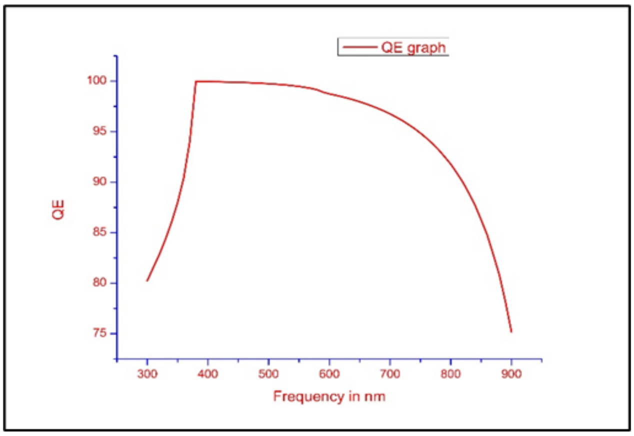

Figure 3. QE curve of PSC

device. Also, we choose ambient temperature as 300k and incident light power1000W/mm^2 for our device and we also take wavelength range 300nm to 900nm for quantum efficiency for our simulation purpose in that paper.
These values show that $MASnBr_3$-based devices can achieve high performance, comparable to some Pb-based perovskites.

Table 3(Derived data from Scaps-1D)

Voc (V)	Jsc (mA/cm^2)	Fill Factor (FF)	Efficiency (η)
0.91	33.1	73.6%	22.1%

IV. CONCLUSION

$MASnBr_3$-based perovskite solar cells demonstrate high simulated efficiency and strong potential for sustainable photovoltaics. Proper band alignment, low interface defect density, and high-quality transport layers are key to performance. Further work should address long-term stability and large- scale fabrication.

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Infrastructural Development of Engineered Landfills

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ABSTRACT

Landfills are widely used for the disposal of various types of waste, including municipal waste, hazardous, chemical, and electronic materials. However, improper management and environmental exposure often compromise their effectiveness. One major issue is the production of leachate—a toxic liquid formed when waste breaks down and mixes with water—which can seep into the soil and contaminate groundwater. Another concern is the generation of landfill gas (LFG), primarily methane and carbon dioxide, which contributes to air pollution and climate change. These environmental hazards not only degrade ecosystems but also pose serious health risks to nearby communities. Therefore, proper landfill design, monitoring, and management are essential to minimize their harmful impacts.

In this paper we will discuss about the Engineered landfills, its effect in nature and ground water and design for a stable long running and effective engineered landfill.

Keywords: Landfill, municipal waste, leachate, climate change, landfill design, Engineered Landfill.

I. INTRODUCTION

Engineered landfills are an essential component of integrated municipal solid waste (MSW) management systems, offering a scientifically structured approach for the long-term disposal of waste. As per the **Municipal Solid Waste Management Rules, 2016** issued by the **Ministry of Environment, Forest and Climate Change (MoEF & CC)**, landfills must incorporate engineered features such as bottom liners, leachate collection systems, gas venting, and final capping mechanisms. These systems are designed to minimize environmental contamination and enable post-closure care for extended periods.

According to the **CPHEEO Manual on Municipal Solid Waste Management (2016)**, engineered landfills in India should have a design life of **20–25 years**, with provisions for phased construction, buffer zones, and minimum distances from sensitive receptors (e.g., 20 km from airports or airbases). The landfill base must be sloped between **1–2%** to facilitate leachate drainage, while embankment side slopes are generally maintained at **1V:3H** for internal stability.

Geotechnical characterization plays a pivotal role in landfill site selection and design. **Joshi and Ahmed (2016)** highlight the importance of in-situ testing and laboratory analyses, including grain size distribution, Atterberg limits, compaction (Proctor) tests, permeability tests (acceptable permeability ≤ **1×10^{-7} cm/s**), and shear strength parameters (cohesion > 25 kPa, angle of internal friction > 25°). These parameters ensure adequate bearing capacity and containment integrity. The **Landfill Engineering Guide** by **ISWA (2022)** further elaborates on the use of **composite liner systems**, combining **HDPE geomembranes** with **compacted clay layers**, and emphasizes the importance of installing **daily, intermediate, and final covers** for operational control.

Gandhimathi et al. (2013) also underscore the need for pre-treatment and segregation of waste before landfilling to reduce the burden on landfill space and enhance system performance. The use of the **3R approach** (Reduce, Reuse, Recycle) and strategic site planning significantly contributes to the sustainability of landfill operations.

In summary, the reviewed literature confirms that engineered landfills, when developed in compliance with national standards and reinforced by rigorous geotechnical investigations, provide an environmentally sound and sustainable solution for long-term waste disposal.

II. INTRODUCTION

Waste management is a growing global concern due to the continuous rise in solid waste each year. In the 1990s, developed countries generated up to 800 kg of waste per person, while developing countries produced up to 200 kg per person. By 2010, global solid waste reached about two billion tons, with developed nations contributing around half. However, this is expected to shift as urban populations grow in developing regions. By 2035, countries in Asia and Africa are predicted to double their waste output, while developed nations are expected to reduce theirs.

Landfills, which are specially designed sites for burying solid waste, play a key role in waste disposal worldwide. Most of the waste they receive includes everyday items like packaging, food scraps, furniture, batteries, and clothing. The use and management of landfills vary significantly across countries. For example, Sweden sends none of its municipal solid waste (MSW) to landfills, while nearly all of Bulgaria's MSW ends up in landfills. In 2014, 41% of Europe's MSW went to landfills. In contrast, many Asian countries rely on open dumping and burning, with little regulation. In the U.S., over 50% of waste was landfilled in 2015.

Figure 1: An Engineered Landfill settling down

Despite the different approaches to waste disposal, landfilling remains one of the most common methods. Engineered landfills, also known as sanitary landfills, are carefully designed waste disposal sites that use advanced engineering methods to manage and contain waste. These landfills include systems to control surface water through proper drainage, compact waste into thin layers, and cover it with soil to reduce exposure. They also feature leachate collection systems that channel the liquid waste into treatment lagoons or similar facilities, as well as vents to safely release landfill gases. A key aspect of engineered landfills is their planned isolation from surrounding geological features to prevent contamination and promote safe stabilization of waste.

The primary goal of sanitary landfills is to isolate waste from the environment and minimize its harmful effects through physical, chemical, and biological processes. These landfills are built with protective liners at the base and involve strict planning from site selection to post-closure monitoring. Waste is compressed and layered to speed up decomposition and reduce space usage. Because of their regulated design and operation, engineered landfills are considered the safest method for waste disposal, with the lowest risk to public health and the environment.

III. ILL - EFFECTS OF LANDFILL IN NATURE

Landfilling, while widely used for waste disposal, poses several environmental challenges that can have both immediate and long-lasting consequences. The key impacts include:

- **Soil and Water Contamination:** One of the most critical environmental risks of landfilling is leachate production. This toxic liquid, formed when rainwater filters through waste, often carries hazardous substances such as heavy metals, organic pollutants, and chemicals. If not properly managed, leachate can seep into the surrounding soil and groundwater, threatening ecosystems and contaminating drinking water sources.
- **Air Pollution and Greenhouse Gas Emissions**: As organic waste decomposes in landfills, it generates methane—a greenhouse gas over 25 times more potent than carbon dioxide. In addition to methane, landfills release other pollutants like VOCs and carbon dioxide, which contribute to air pollution, unpleasant odors, and climate change.

Figure 2: Landfill effects in nature

- **Loss of Biodiversity:** Constructing landfills typically involves clearing land, which can lead to the destruction of natural habitats. This disrupts local ecosystems, displaces wildlife, and threatens plant species. Moreover, animals that scavenge landfill sites may suffer injuries or death from ingesting or becoming entangled in plastic and other waste materials.
- **Visual and Aesthetic Degradation**: Landfills are often considered eyesores. Their presence can significantly reduce the visual appeal of surrounding areas, impact tourism, and lower the value of nearby residential and commercial properties.

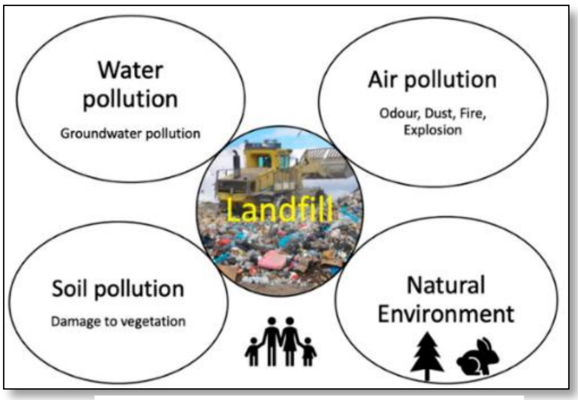


Figure 3: Landfill Impact on Nature

- **Resource Depletion**: Landfilling often involves discarding items that could otherwise be recycled or composted, such as plastics, metals, food waste, and paper. This not only contributes to the depletion of natural resources but also increases the environmental burden of producing new materials.

- **Soil Degradation and Land Use Issues**: The compaction of waste and covering layers used in landfills alter the physical and chemical properties of soil. This degradation reduces soil fertility and structure, making the land unsuitable for agriculture, reforestation, or natural vegetation even after the landfill is closed.
-

IV. LEACHATE CONTAMINATION IN GROUNDWATER

Leachate contamination of groundwater is one of the most serious environmental risks associated with landfills. Leachate is the liquid that forms when rainwater or other moisture percolates through waste material, picking up dissolved and suspended contaminants along the way. Here is a breakdown of how it affects groundwater:

- **Formation of Leachate**: When water passes through waste layers in a landfill, it absorbs organic and inorganic substances, including heavy metals, pathogens, and chemicals, creating a highly contaminated liquid known as leachate.
- **Inadequate Liner Systems**: In older or poorly designed landfills, the bottom liner—meant to contain leachate—may be absent, damaged, or ineffective, allowing the leachate to seep into surrounding soil and reach groundwater supplies.
- **Chemical Contaminants**: Leachate may contain hazardous substances such as lead, mercury, arsenic, ammonia, and nitrates, which are toxic even at low concentrations and can pose significant health risks to humans and wildlife.
- **Pathogen Transmission**: Biological contaminants including bacteria, viruses, and parasites can be present in leachate, potentially making groundwater unsafe for human consumption or agricultural use.
- **Long-Term Contamination**: Once groundwater is polluted, cleanup is extremely difficult and costly. Contaminants can persist for years, spreading through aquifers and affecting large areas beyond the landfill site.
- **Human Health Hazards**: Contaminated groundwater can lead to serious health issues such as gastrointestinal infections, kidney damage, reproductive problems, and even cancer if consumed over time.
- **Impact on Ecosystems**: Groundwater-fed rivers, lakes, and wetlands can also be affected, leading to broader ecological damage, including harm to aquatic species and plants dependent on clean water sources.

Side Effects of Leachate-Contaminated Groundwater

- **Human Health Risks**
  - Contaminated groundwater can carry harmful chemicals and pathogens.
  - Prolonged exposure may lead to serious health problems such as:
    - **Gastrointestinal diseases** (from bacteria and viruses)
    - **Kidney and liver damage** (due to heavy metals like lead, cadmium)
    - **Reproductive and developmental issues**
    - **Increased risk of cancer** (from long-term exposure to carcinogenic substances)
- **Unsafe Drinking Water**
  - Leachate pollutes underground water sources, making it unsafe for household use without extensive treatment.
  - This can severely affect rural and urban communities that rely on groundwater as their primary drinking source.

1. **Agricultural Impact**
   - Use of contaminated groundwater for irrigation can lead to:
     - Accumulation of toxins in crops

- Reduced soil fertility
- Poor crop yields and food safety concerns

2. **Damage to Aquatic Ecosystems**
   - Polluted groundwater can reach rivers, lakes, or wetlands, disrupting aquatic habitats.
   - Toxic substances can harm or kill fish, amphibians, and aquatic plants.
3. **Loss of Biodiversity**
   - Contaminated groundwater affects flora and fauna dependent on clean water.
   - Long-term exposure can lead to the decline or extinction of sensitive species in the area.
4. **Economic Consequences**
   - Cleanup and remediation of polluted groundwater are expensive and time-consuming.
   - Communities may face losses in agriculture, tourism, and increased healthcare costs.
5. **Public Distrust and Social Impact**
   - Persistent groundwater contamination can lead to public fear and reduced trust in local waste management and government agencies.
   - May cause displacement of communities and affect property values.

V. DESIGN OF A STABLE ENGINEERED LANDFILL

A. Site Selection for any Engineered Landfill :-

1. Available Land Area

o The site must be large enough to accommodate current and future waste volumes, including space for operations, access roads, and buffer zones.

2. Effect of Waste Processing and Resource Recovery

o Consider how much waste will be diverted due to recycling, composting, or energy recovery, which affects the size and lifespan of the landfill.

3. Haul Distance

o The distance from waste generation points (like cities) to the landfill should be minimized to reduce transportation costs, fuel use, and emissions.

4. Soil Conditions and Terrain

o The site should have stable, low-permeability soil (like clay) to reduce the risk of leachate leakage. A naturally favorable topography can reduce construction costs and improve drainage.

5. Climatic Conditions

o Weather patterns like heavy rainfall, high winds, or extreme temperatures can influence landfill performance and environmental impact, especially in terms of leachate and gas generation.

6. Surface-Water Hydrology

o Proximity to rivers, lakes, or flood zones must be assessed to prevent surface water contamination and manage stormwater effectively.

7. Geological and Hydrogeological Characteristics

o The subsurface composition (rock, soil types) and groundwater depth are crucial for assessing the risk of leachate migration and ensuring long-term containment.

8. Local Environmental Sensitivity

o The site's proximity to protected ecosystems, wildlife habitats, and biodiversity hotspots must be evaluated to avoid ecological damage.

9. **Potential for Future Land Use**

o After closure, the site could be repurposed for parks, solar farms, or green spaces. The long-term usability of the land should be factored into planning.

B. Soil Investigations of an Engineered Landfill:-

For engineered landfill in India, soil investigations include borehole drilling, SPT/CPT, groundwater level monitoring, and in-situ permeability tests, followed by laboratory testing of collected samples. Key parameters and their standard allowable values are: **permeability** of subsoil or compacted clay liner should be **≤ 1 × 10^{-7} cm/sec; plasticity index (PI)** should be **> 15** for clay used in liners; **maximum dry density (MDD)** and **optimum moisture content (OMC)** must be established through Proctor tests to ensure proper compaction**; shear strength** must be sufficient to maintain **embankment and slope stability,** typically requiring **cohesion (c) > 25 kPa** and **angle of internal friction (ϕ) > 25°**; and **Atterberg limits, grain size distribution,** and **specific gravity** help in soil classification and suitability assessment. Additionally, the **water table** should ideally be **at least 2 meters below the base of the landfill** to prevent contamination risk.

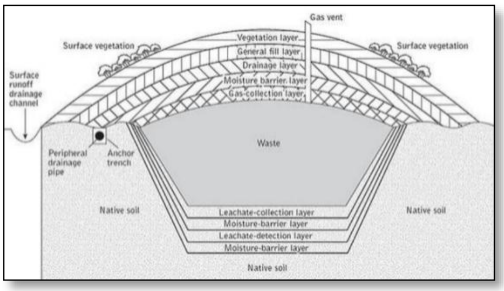


Figure 4: Cross section of a landfill.

C. Soil Stabilization (Cement Stabilization) of an Engineered Landfill:-

Cement stabilization is a well-established technique in geotechnical engineering for enhancing the strength and durability of weak soils, especially in the construction of engineered landfills and embankments. The process involves pulverizing the soil layer, adding an appropriate quantity of cement (typically 3–10% by weight), mixing it uniformly, compacting the mixture, and curing it to achieve the desired engineering properties. As per Indian guidelines such as **IRC:SP:89-2018** and **IS 2720 (Part 5 & 10)**, soils suitable for cement stabilization must meet certain criteria. These include a plasticity index (PI) generally less than 20%, liquid limit (LL) under 40%, organic content below 2%, pH between 5.5 and 8.0, and sulfates (as SO_3) limited to around 1% to avoid expansive reactions.

In a practical engineered landfill application involving industrial or chemical waste, preliminary mixing tests with **Portland Slag Cement (PSC)**, conforming to **IS 455:2015**, showed that adding 10% cement by weight significantly improved the consistency of waste material—from a soft to a stiff state. Field implementation was carried out at designated stabilization units on-site, which were equipped with cement silos and twin-shaft continuous mixers operating at a capacity of 50 tons per hour. Waste was excavated, transported to these units, stabilized with cement, and subsequently transferred to the landfill cell for structured placement.

To evaluate the strength parameters of the stabilized material, **direct shear tests** were performed in accordance with **IS 2720 (Part 13):1986**. Cuboid samples (60 mm × 60 mm × 18 mm) were tested under normal stresses of 50, 100, 150, 200, and 250 kPa. Shear strength was calculated using the **Mohr-Coulomb failure criterion**:

$\tau = \sigma \cdot \tan(\phi) + c$

where:

- τ = shear strength (kPa)
- σ = applied normal stress (kPa)
- ϕ = angle of internal friction (degrees)
- c = cohesion (kPa)

The equipment used dial gauges with an accuracy of 0.01 mm and a constant strain rate of 0.05 mm/min. Measurements were recorded every 30 seconds. The test continued until the peak shear force remained constant or dropped by less than 10% over three consecutive readings, or until a maximum deformation of 10% was reached. Peak shear strength was also derived using:

$\tau = Q_{max} / A$

where Q_{max} is the peak shear force (N) and A is the shear area (mm²). The final objective was to confirm a **Stability Factor (SF) ≥ 1.5**, ensuring that the stabilized waste met the safety and performance requirements for landfill inclusion, based on numerical modeling using the **finite element method (FEM)**.

D. Clay – fly ash liners

In engineered landfills, long-term leachate migration through containment systems is a persistent challenge. As such, there is a growing interest in developing environmentally sustainable liners that can offer both physical and chemical resistance over extended periods. One promising solution is the use of **clay–fly ash geopolymers**. These materials combine the natural abundance and adsorption properties of clay with the high performance of fly ash-based geopolymers, providing a sustainable alternative for leachate attenuation.

Geopolymers synthesized from **class-F fly ash** and activated with **sodium hydroxide (NaOH)** have demonstrated excellent properties such as high early strength, reduced shrinkage, long-term durability, freeze-thaw resistance, and effective containment of pollutants. The key to their effectiveness lies in the chemical composition—especially the presence of **silica, alumina, and iron oxides**, and the low content of calcium oxide—which enhances both **attenuation capacity and chemical stability**.

Furthermore, **clay** acts not only as a physical barrier but also participates in the **geopolymerization process** due to its aluminosilicate content, contributing to the formation of a durable and impermeable matrix. The performance of clay–fly ash geopolymers is significantly influenced by various factors including the **type and proportion of raw materials**, **activator concentration**, **water content**, **curing conditions**, and the nature of **target contaminants**. Adjusting these parameters allows for tailoring the material to achieve **optimal porosity, conductivity, and contaminant retention** properties. Thus, clay–fly ash geopolymers present a **viable and sustainable liner solution** for modern engineered landfills, combining environmental compatibility with strong physical and chemical performance over the long term.

E. Landfill Liner and Cover Systems – Role of Geosynthetics :-

Geosynthetics are synthetic materials, often polymer-based, that are used in civil engineering applications, particularly in landfills, to improve performance and environmental safety. Common polymers include **polypropylene, polyethylene, PVC, polyester, nylon**, and **chlorinated polyethylene**. These materials are manufactured into various forms depending on their function and application in the landfill system. The primary types of geosynthetics used in engineered landfills are:

- **Geotextiles: Permeable fabrics used in separation, filtration, and reinforcement.**
- **Geomembranes: Impermeable sheets primarily used as barriers to liquid and gas movement.**
- **Geonets: Net-like structures used for drainage.**
- **Geocomposites: Combinations of two or more geosynthetic types to perform multiple functions.**

Geosynthetics in landfill liner and cover systems perform five key functions.

Separation prevents mixing of soil or waste layers by placing geotextiles between subgrade and aggregate, maintaining structural integrity.

Reinforcement improves mechanical strength using high-strength geotextiles or geogrids, especially on side slopes, enhancing stability and enabling steeper, cost-effective designs.

Filtration allows water passage while retaining soil particles; geotextiles placed between waste and drainage layers prevent clogging, improving leachate system lifespan.

Drainage is achieved through geonets and geocomposites that transport leachate or gas to collection points, reducing seepage risks.

Finally, **moisture barriers** like HDPE geomembranes act as impermeable liners and caps, effectively containing leachate and landfill gases to protect groundwater and the environment.

Figure 3: Geomembrane installation

VI. WORKING PROCEDURE AT SITE

While starting the project/ site of an engineered landfill, first a proper area should be selected maintaining the Municipal Waste Management rules. Landfill sites must be located at a safe distance from habitation areas, forests, water bodies, monuments, National Parks, wetlands, and places of significant cultural, historical, or religious value. A buffer zone with no development should be maintained around the site and integrated into the city's land use and town planning frameworks. Additionally, the site must be situated away from airports and airbases; if it is within a 20 km radius of such facilities, prior approval from the respective authorities is mandatory.

Whenever feasible, landfill locations should be chosen near waste processing facilities. If not available nearby, the development of such a facility must be included as part of the landfill project. The site should be sufficiently large to meet disposal needs for 20 to 25 years. It should also include detailed documentation outlining a phased construction strategy and a comprehensive closure plan.

Landfills that have been in continuous use for over five years must be upgraded to meet the current regulatory and environmental standards specified in the relevant guidelines. All the soil test parameters should be followed as discussed earlier.

The earth cutting will be done for an area of 100 x 100 sq. m and 6-8 mtr. deep providing embankment in all four sides with a slope of 1:2.5 and at bottom 1:75 slope should be provided for better drainage. (always consider the drawing while working)

The soil stabilization is very much required in these cases as the solid wastes dumped in the landfill can deploy the soil status and total landfill system can collapse. Here, Cement stabilization of soil will be done. It enhances the strength and durability of weak soils, especially in the construction of engineered landfills and embankments. The process involves pulverizing the soil layer, adding an appropriate quantity of cement (typically 3–10% by weight), mixing it uniformly, compacting the mixture, and curing it to achieve the desired engineering properties. After stabilizing the soil, a 900mm thick layer of clay – bentonite – flyash mixture of 62:18:20 ratio will be applied. Then a 1.5mm thick High density polyethene (HDPE) layer should be provided although. After this 280 GSM Geotextile is covered maintaining the proper slope.

A drainage layer of 300mm by clay – flyash mixture (75:25 ratio) will be established with 150mm dia PVC pipes containing pebbles out side acting as net for smooth passing of fluid. This drainage layer is provided for passage of leachate. Again a 280 GSM Geotextile is covered.

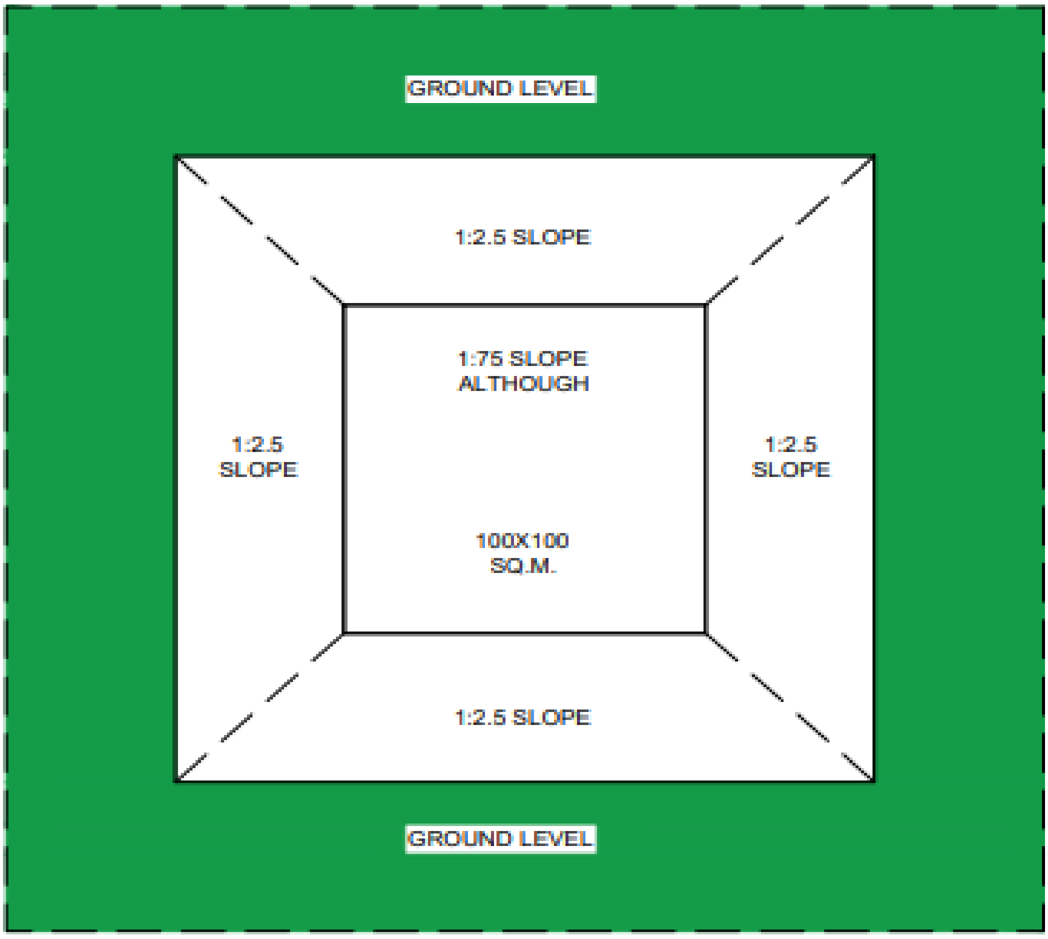
After all these layers are done, waste dumping starts. Here the waste mount will be 60m high, the waste should be compacted at least 2 times a day; slowly it will take a shape of a mount with a natural slope. The life span of waste dumping in this landfill will be 8years 3 months. Once it reaches the age limit the capping work will begin and it should be completed within 6-9 months. The capping undergoes different layers :

- 150mm Soil layer
- 400mm thick layer of clay – bentonite – flyash mixture of 62:18:20 ratio
- 200 mm thick drainage media made with clay, 100mm dia PVC pipes.
- 400mm soil layer with grass breeding and vegetation.
- Overall from the ground level to the top waste mount, a slope of 1:3 should be maintained.
- At least 5 gas venting pipes should be installed.

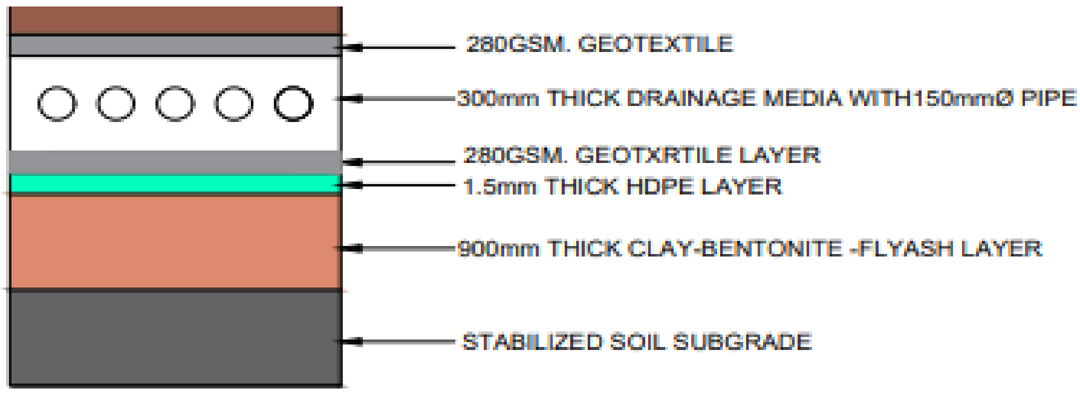
Figure 4: Gas Vent Pipe in a landfill

*Note: Always follow the drawings provided while working.

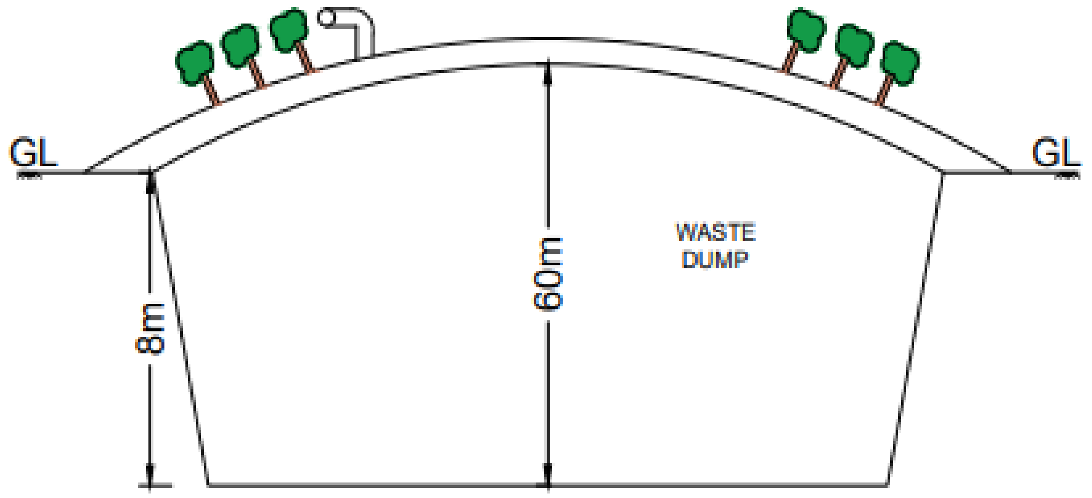
DRAWINGS



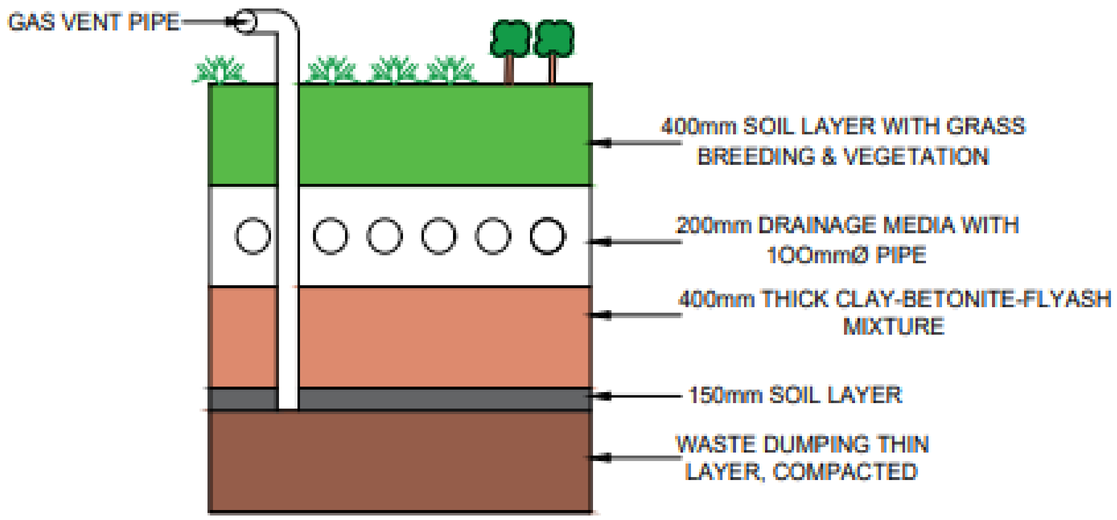
PLAN



BOTTOM LINER



ELEVATION OF THE ENGINEERED LANDFILL AFTER CAPPING & VEGETATION LAYER



TOP LINER

VII.CONCLUSION

Engineered landfills are scientifically designed systems that ensure safe, long-term disposal of solid waste with minimal environmental impact. By incorporating proper site selection, soil investigations, liner systems, leachate and gas management, and long-term monitoring, they provide a sustainable solution to waste management challenges. Their success depends on strict adherence to technical standards, regulatory guidelines, and ongoing maintenance to protect soil, water, and air resources

Here the landfill is designed for a time period of 30-35 years. The main objective of this project is to design a stable landfill which does not become a check for heathy ground water and as well as humans.

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Review on Revolution of Green Steel Sustainable Practices for the Future of Manufacturing Industry

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ABSTRACT

Sustainability has become a necessity in order to battle the rising levels of global warming and ensure that resources are not over-used. Steel, being recyclable, seismic resilient, and cost-efficient, is a formidable contributor to green construction. Since steel production generates significant carbon emissions, it is crucial to explore sustainable methods for producing steel. The review elucidates the importance placed by eco-industry practices on environmental preservation, particularly in the production of steel. Green building initiatives are, thus, accepted in the construction domain – the era of energy efficiency and reduction in carbon emissions. Similarly, industries should improve their environmental compliance alongside productivity. Sustainable enterprises, such as those developed by minimizing waste and maximizing energy conservation, are in the essence of environmental protection. Sustainability in the automobile industry is gaining thereby. The light weighting in eco-friendly vehicle manufacturing is another version of that. The idea further corroborates the necessity to overhaul industries for a greener and sustainable future.

Keywords: Global warming, Green building, Sustainability, Light weighting, Sustainable future

I. INTRODUCTION

The population created a surge in energy and material demand, with concomitant environmental effects: increased generation of solid wastes, vehicular and industrial emissions, and contamination of surface and groundwater reservoirs [1]. Greenhouse gas (GHG) emissions have been globally accepted to be a major factor in global warming; sources include natural as well as anthropogenic effects [2]. As environmental concerns mount in the world, contemporary societies are inclined to look along sustainable lines to reduce emissions and maximize energy and natural resource utilization. Recent years have thus seen a shift in the national and international agendas towards the creation of a sustainable environment through environmentally friendly production processes [3]. The term "sustainable development" came into common use after the 1987 publication of *Our Common Future*, also known as the Bruntland Report. This report defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [4].The word "sustainable" is generally used to imply efficacious and improved procedures rendering social, financial, and environmental benefits, and ensuring the conservation of our limited resources. Environmentally conscious production involves the manufacture of goods through processes that diminish potentially unfavorable environmental impacts, conserve energy and natural resources, work for the well-being of workers, local communities, and consumers, and at the same time ensure economic viability [5,6].

The building industry contributes to increasing carbon emissions in several ways, including producing primary materials and transporting finished products. The production of raw materials, like cement and steel, or chemicals, can add substantially to CO2 emissions [7]. To illustrate, the World Steel Association reports that the industry is responsible for 7-9% of the world's carbon emissions each year [8]. Today, steel is used in various industries, such as construction, manufacturing, automotive, and healthcare because of its durability, versatility, affordability, resistance to oxidation, and appearance. As depicted in Fig. 1, the civil construction sector consumes the majority (52%) of globally produced steel, driven by the demand for larger and more advanced structures. This widespread usage prompts a critical examination of steel's environmental footprint throughout its lifecycle. Structural systems, comprising a significant portion of a building's embodied energy, serve as a vital indicator for evaluating environmental impacts and facilitating comparisons among different materials and construction techniques [9-11]. Steel production makes a massive contribution to the global economic development and the well-being of humanity [12]. The production rate is always increasing [13]. Though energy efficiency and optimization have improved in recent decades, the steel industry still accounts for over a quarter of CO2 emissions, making it an important contributor to climate change [14]. Steel is a sustainable material and steel framed structures can provide compelling solutions with performance positives over their entire life cycle, with environmentally friendly building characteristics that stem from steel's sustainable materials [15].

Green buildings and sustainable construction practices have received increasing scrutiny to help reduce GHG emissions, and their effects. The use of techniques such as Life Cycle Assessment (LCA) [16,17] can help to understand the damage caused by the GHGs and to evaluate improvement options.

The paper examines the need for sustainability in a growing steel production sector, which is a fundamental heavy industry across the world. The growth of urbanization and cities encourages greater demand for steel for construction, and this is fundamentally important for countries in their development. The conversation also covers the potential of green construction methods in the steel industry and green adoption of steel in the automotive industry, indicating a shift towards more environmentally friendly practices in industries that have traditionally demanded resources.

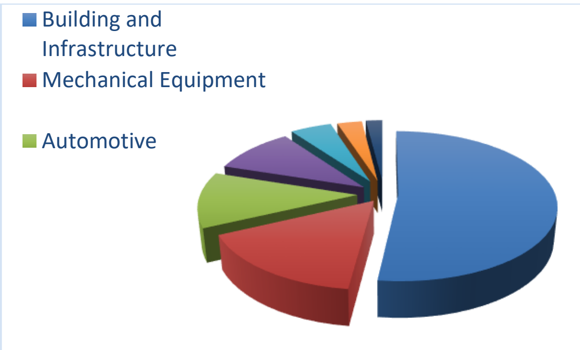

Fig. 1 Yearly production of crude steel categorized by industrial consumer sectors

II. GREEN PRACTICES IN STEEL PRODUCTION

The necessity for steel is ever-increasing at a global level, thus the production goes up worldwide according to Figure 2. In a decade, from 2011 to 2021, the need for steel in the world went from 1540 to 1951 million tons which is an increase of 26.5% [18]. The achievement of sustainable steel production is one of the main global challenges and has a lot in common with cement production. We discuss below the various sustainability indices related to steel development and the cutting-edge achievements in this area.

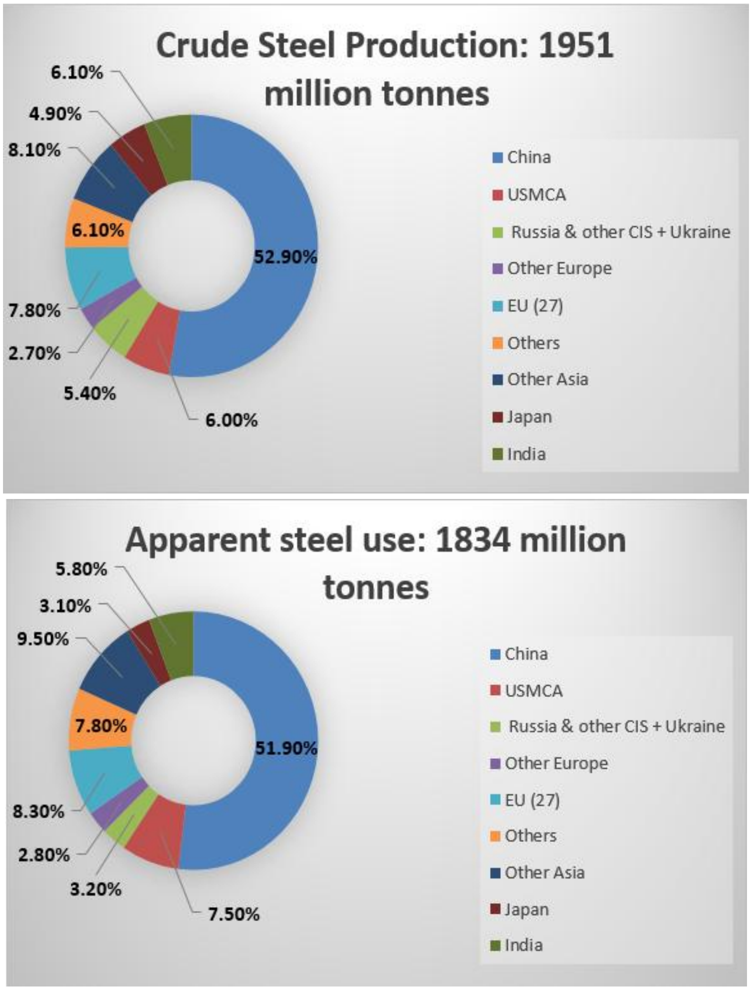

Fig. 2 Worldwide steel production and use by 2021[18]

A.Mitigation of Carbon Dioxide Emission

Ejection of gases and energy consumption represent primary environmental issues in steel production. The steel industry emits approximately 997 kg of CO_2/ton of steel, contributing 4 to 5% of worldwide CO_2 releases. Over 60% of the total CO_2 discharges from the steel sector occur prior to steelmaking [19]. It is safe to say that the CO_2 emissions generated from the electric arc furnace [EAF] process to recover the steel are minimal as opposed to other technologies. With the aim of diminishing CO_2 discharges by industry, the steel industry has been developing and introducing advanced technologies in its processes through programs like the Asia-Pacific Partnership on Clean Development and Climate. Steel contributes to the reduction of carbon dioxide emissions through a) the use of lightweight design, b) the lengthening of product life, and c) recycling. A 5.1% reduction in fuel consumption and a 5.7% reduction in GHG discharges can be achieved through lightweight steel [20].

Application of AHSS as a substitute for the common steel results in the decrease of the life cycle emissions of 156 million CO2 equivalents [21]. Steel products, such as buildings, industrial machinery, and rail, exhibit extended lifespans, contributing to lower net carbon dioxide emission [22].
Utilizing biomass in steel manufacturing substantially decreases CO2 emissions. Alternative fuels like synthetic natural gas generated from biomass or bio-hydrogen have the potential to replace liquefied petroleum gas in reheating furnaces and can also be utilized as injection gas in blast furnaces [23]. In the steel industry, reductions of greenhouse gas emissions can be reduced by utilizing charcoal in sintering, injecting torrefied biomass, charging lump charcoal from the zenith, or injecting charcoal fines [24].

B. Steel Scraps Reclamation

On a global scale, steel holds the distinction of being the most recycled material. Through the recycling of steel scraps, there is a notable reduction in net carbon dioxide emissions, as well as decreased consumption of raw materials and energy utilization [25]. Steel scrap comes from three main sources: primary (scrap generated during the process of producing steel), secondary (scrap produced while creating steel products) and tertiary (remnants produced at the end of a steel product's life) [26]. The annual use of steel scrap for steel manufacturing has been trending upward globally, both in total and as a matter of individual steel recyclability. Tertiary steel scrap holds the greatest percentage of recycling in comparison to the other two residuals. Despite the trend of increasing recycled steel, there is a downward trend in relation to total amount of steel scrap used per unit of crude steel produced. In 2010, proportion of scrap utilized in crude steel manufacturing stood at 0.37, whereas by 2014, this ratio had declined to 0.35 [27]. According to the World Steel Association (WSA) in 2010, recycling one ton of steel scrap leads to the preservation of 7 kg of coal, 1200 kg of iron ore, and 51 kg of limestone. This process results in the avoidance of 1800 kg of CO2 emissions [28]. Tests on powder metallurgy techniques utilizing powder derived from industrial steel remnants have demonstrated the superior quality of steel compacts. These compacts were fabricated from ultrafine-grained powder steel [29].

C. Minimization of Energy

The manufacture of steel requires considerable energy input, making up about 15% of total industrial energy consumption [30]. Other aspects affecting the performance of energy efficient steel production include capacity utilization of plant, environmental regulations across countries, and costs such as power and raw materials [31]. The energy expenses of steel formation constitute approximately 20% to 40% of overall valuation of steel fabrication [32]. Approximately half of the total energy demand is sourced from coal, with electricity and natural gas contributing 35% and 5% respectively [33]. Steel formation also incurs varying energy consumption based on the process route, similar to the variation seen in carbon dioxide emissions. Lowering fuel consumption, enhancing the efficiency of hot stoves, and optimizing secondary energy usage, such as utilizing ejection from blast furnace, and maximizing heat capture and application, can minimize energy demand in the blast furnace process. Maximizing bed depth, optimizing energy utilization, minimizing air leakage, and incorporating technologies for waste heat recovery and utilization are essential for enhancing the energy efficiency of the sintering process [34]. Decreasing the iron-to-steel ratio and replacing the blast furnace/basic oxygen furnace [BF-BOF] method to the direct reduction iron based electric arc furnace [DRI-EAF] approach emerge as highly efficient strategies for lowering energy demands in steel production and represents an optimal pathway for reducing energy consumption within the steel industry [35].

III. SUSTAINABILITY OF STEEL IN BUILDING CONSTRUCTION

The progression of the sustainable development movement has been unfolding globally for nearly a quarter-century [36]. The initial delineation of sustainable construction emerged at the inaugural International Conference on Sustainable Building, convened in Florida [37]. This conference concludes that green construction serves as a fundamental facet in cultivating environmental sustainability and involves in ensuring that we preserve the planet in a state conducive to future generations experiencing a quality of life comparable to our own [38]. While definitions of "green buildings" and "sustainability" may differ, these terms are frequently used interchangeably or in tandem. "Green" typically pertains to products, individuals, and environmental effects, whereas "sustainable" has a broader scope encompassing environmental, social, and economic aspects of sustainable development [39,40].

Steel's growing use in office building construction is driven by its minimal environmental impact and numerous eco-friendly attributes. Notably, steel offers nearly complete recyclability, minimal resource utilization, scant waste generation, and structural flexibility. Additionally, energy demands for steel structure fabrication and assembly constitute merely 3% of the building's overall energy consumption throughout its lifecycle [41]. Steel represents the singular structural element capable of undergoing recycling processes [42]. Steel is a substance that operates within a nearly closed-loop material cycle [43,44]. In a closed-loop system, materials are circulated within the life cycle, favoring reuse and recycling over disposal at the conclusion of a building's life span [36]. In ecological building practices, materials should be retained within their respective cycles for as long as feasible. This concept can be applied across two key phases: the design phase and the demolition phase [45,46]. Hence, the enhancement of structural steel reuse and recycling opportunities emerges as a critical concern. The sustainable benefits of steel can be condensed into material efficiency, signifying reduced natural resource utilization, transportation, energy consumption, and emissions and other characteristics discussed in Table 1.

To achieve the goal of sustainable construction, a holistic design framework based on principles of lifetime engineering must be implemented, and with that, a number of frameworks have been created such as LCA (Life-cycle assessment)(Bio-based sustainable construction, 2020); LCC (Lifecycle costing) (Alshini et al, 2021); and LCP (Life cycle performance)(Idorn et al, 2022).

TABLE 1:Qualities of steel in Eco-Friendly Construction

Qualities	**Evaluation of Steel Building**
Operability	Construction of steel utilizes streamlined factory processes, conserving resources while enabling the construction of expansive, tall, and versatile buildings.
Speed	Steel frameworks are swiftly assembled on location, thereby minimizing local disturbances.
Weight	Steel structures, being lightweight, enhance efficiency in materials, energy, transport, and emissions, while also allowing for vertical expansion and flexible location options.
Waste	Steel constructions exhibit high material efficiency, generating minimal waste, with the majority being recycled.
Performance	Steel, crafted with precision through advanced computerized technology, boasts high performance.
Logistics	Steel constructions arrive at the site precisely whenever required for setup and can be produced domestically.
Durability	Steel constructions are of exceptional quality and possess long lifespans.
Health	Construction of steel offers pre-fabricated assembly, low-emission substance, regulated procedure, and ensures high-quality architecture.
Recyclability	Steel is recyclable without any loss in quality.
Reusability	Components of steel buildings can be disassembled and repurposed.

In assessing the sustainability of steel structures, there are four life cycle stages: Design, Construction, Operation and Maintenance, and End-of-Life. Each stage is critical to appraising the sustainability of steel structures (for more detail see Figure 3. Sustainability Criteria in the Life Cycle of Steel) (Galante, 2109). Attaining sustainable buildings is not a response to one material or discipline, it is a multi-faceted problem that will require a multi-disciplinary and holistic life cycle view to inform decision making. For steel, the journey of enhancement and innovation towards sustainable construction is an iterative process that never truly stops.

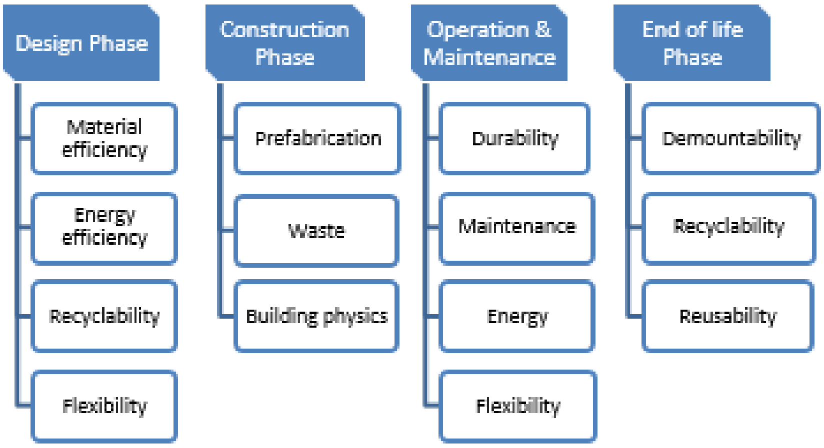

Figure 3: Sustainability Criteria in the Life Cycle of Steel [39]

After the completion of construction, corrosion can ensue, resulting in diminished structural capacity. This process also signifies the squandering of the carbon dioxide initially invested in the structure's production [53]. In the pursuit of curbing carbon dioxide emissions, there is contemplation regarding the incorporation of embodied energy metrics for construction materials. A key aspect of this consideration is the loss of embodied energy through corrosion and deterioration across the lifetime of a structure. In the SAP process to prevent steel corrosion, alloying processes are incorporated with each of the different alloying materials. Table 2. provides a range of alloying elements and some of their associated effects on steel manufacturing processes.

TABLE 2: Steel alloying using diverse materials and their effects on corrosion prevention

Alloying Material	Effects of Alloying
Nickel	Enhances resilience in cold environments, while also delivering metallurgical and thermal stability, weldability, hardenability, and resistance to CO2 corrosion, stress corrosion cracking of sulphide and chloride [54].
Chromium	Enhances resilience against oxidizing corrosives, Oxidation and sulfidation at elevated heat, while also enhancing resilience against pitting and localized oxidation, and improving hardenability and strength [55].
Molybdenum	Enhances resilience against pitting and localized oxidation in Cl-rich aqueous condition, while contributing to heightened high-temperature strength and minimizing temper embrittlement [55].
Iron	Enhances resilience against condition conducive to elevated heat carburizing, reduces alloy expenses, and manages heat expansion [56]
Copper	Enhances resilience against reducing acids and salts, with copper additions enhancing resistance to specific acids in nickel-chromium-molybdenum-iron alloys [57].
Aluminum	Enhances resilience against oxidation at high temperatures and facilitates age hardening [55].
Titanium	Binds with C to diminish vulnerability to oxidation along grain boundaries caused by Crl3 precipitation from heat treatments, while also augmenting age hardening [55]
Niobium (Columbium)	Combines with carbon to mitigate oxidation along grain boundary, enhances resistance to pitting and localized oxidation, and improves elevated heat resilience [55].
Tungsten	Enhances resilience against reducing acids and localized oxidation, while also bolstering both resilience and ability to weld [59].
Cobalt	Offers heightened high-temperature strength and resilience against carburization and sulfidation [58]

IV. ADVANCING GREEN STEEL IN THE AUTOMOTIVE SECTOR

There has been a significant change in the car industry with the common use of advance high strength steel replacing older low carbon steel, that highlight the usual and perhaps increasing need to use HSS in car manufacturing. Given its properties of: excellent toughness, strength and versatility, steel is the most significant material in automotive manufacturing, serving multiple purposes, from framing to bodywork, to various engine parts and fasteners, [60,61]. It is a lightweight material and advanced high strength steel can be produced thinner because it has more strength, it can provide weight savings in the range of 20%-30% for commercial vehicles [62]. The weight of an automobile is a critical consideration in its design, as vehicle mass directly impacts the level of fuel utilization [63]. Typically, a decrease of 10% in vehicle weight yields a 6–8% enhancement in fuel efficiency [64]. Regarding exhaust emissions, a 5% decrease in body weight correlates with a decrease of 1.3%-1.8% in CO_2 emissions, while a 10% decrease in vehicle body weight increases this to 2.7%-3.6% [65]. Therefore, it is projected that a significant proportion of the body-in-white structure of conventional vehicles will integrate the most recent iteration of AHSS, signifies a shift from the pattern observed where AHSS utilizations reached their zenith in recent times. [66]. The transition towards environmentally-friendly manufacturing in the automotive industry is easier due to the potential adoption of green steel. This is driven by the fact that vehicles heavily utilize primary steel, the automotive supply chain is less complex than construction, and the cost increase for green steel vehicles is minimal, enabling financial feasibility for both manufacturers and customers. [67].

The steel industry emerges as the foremost contributor to CO_2 emissions among manufacturing industries [68]. Addressing GHG ejections from this sector poses a significant obstacle in combating environmental degradation, yet this too signifies a substantial prospect for the progression of eco-friendly steel fabrication. The greenhouse gas emissions intensity associated with BF-BOF method exceeds that of scrap-based EAF technology by 3.5 times and that of DRI-EAF method by 1.4 times [69]. [69] So that, Various steelmaking techniques result in different levels of GHG emissions. Also, several research findings have indicated that recovery of waste heat energy at elevated temperatures in conjunction with carbon capture and storage (CCS) stands out as effective approach for mitigating discharge of GHG in steel manufacturing [70,71]. Transitioning steel production to electric arc furnace (EAF) technology powered by renewable energy sources has the potential to decrease greenhouse gas emissions by as much as 95% in comparison to coal-fired blast furnace operations [72,73]. Moreover, incorporating biomass into the iron and steelmaking process, via techniques like employing charcoal as a reducing agent or introducing biogas injection, offers an additional avenue for reducing greenhouse gas emissions.

V. CONCLUSION

In conclusion, the steel production industry is inherently unsustainable in its continued contribution to the world's carbon emissions. We need to focus on sustainable practices in every aspect of production and further contribute to limiting environmental problems that we continually face. Include ways to reduce CO_2 emissions, including enhancing steel recycling, and investing in energy reduction methods and initiatives. The industry must take these operational steps towards sustainability to also preserve the environment.

In addition, there is potential to achieve environmental mitigation by focused stakeholder interest in transitioning to sustainable steel in both construction and automotive industries.Utilizing steel's durability, recyclability, and versatility should help to lower materials use while advancing innovation and resilience in the marketplace. Not only does this shift have great potential for our environment, but it is good for our economy and for social development.

However, promoting the production and use of green steel entails a great deal of collaboration, across various stakeholder groups, including policymakers, industry leaders and consumers.We can advance green steel with net zero even faster if we all work together collaboratively through cross-sector initiatives and technology transfer while supporting enabling regulatory frameworks. We must collectively transition to a green revolution to achieve environmental stewardship, economic prosperity, and social inclusion. It is important that we create a different paradigm in the steel production process, which means that the transition to sustainable practices must include a shift towards stewardship, a culture of responsibility and innovation. Thus, we need to leverage our steel production to make a positive change, working towards a more resilient and sustainable world for the future generations.

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A Comparative Study of Microstructural Alterations and Mechanical Performance of IN718 Welds : Insights from Diverse Welding Processes

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ABSTRACT

Inconel 718 (IN718) is a widely used nickel-based superalloy known for its excellent mechanical properties and corrosion resistance at elevated temperatures, making it ideal for aerospace and industrial applications. The microstructure of Inconel 718 is crucially influenced by its chemical composition and heat treatments, impacting its weldability and mechanical properties. Precipitation of phases like γ' and γ'' enhances strength, while variations in grain size affect the laser welding response. Challenges in weldability stem from susceptibility to hot cracking in the heat-affected zone due to grain boundary liquation and the segregation of elements. Effective management of pre- and post-weld heat treatments, along with appropriate filler materials, are essential to mitigate these issues. This review provides a comprehensive comparative study of the microstructural alterations and mechanical performance of IN718 welds produced by various welding processes. The study synthesizes findings from multiple research articles, elucidating how each welding technique influences the weld microstructure, particularly in terms of grain size refinement, phase transformations, and formation of detrimental microstructural features such as Laves phase and heat-affected zone (HAZ) characteristics. The insights gained from this comparative analysis aim to guide the selection of appropriate welding processes for IN718 applications, ultimately enhancing the performance and reliability of welded components in critical environments. This comprehensive review serves as a valuable resource for researchers and engineers seeking to optimize welding parameters and improve the quality of IN718 welds.

Keywords: Inconel 718; Microstructure; Weldability; Mechanical Property; GTAW; EBW; Laser Welding; SLM

I. INTRODUCTION

Superalloys are alloys that retain their structural, surface, and property stability at high temperatures, high stress levels, and harsh environments. They are rich in at least one of the elements nickel, cobalt, and iron. [1,2,3] Inconel 718 is a nickel-based superalloy widely employed in aerospace and other high-demand applications due to its exceptional high-temperature strength and corrosion resistance [4].

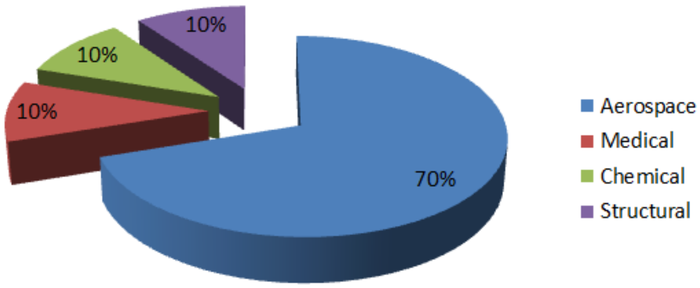


Fig. 1: Commercial Consumption of Nickel Based Superalloy [5]

Over the previous 20 years, the gas turbine engine's propelling force has increased by 60% while fuel consumption has decreased by 20%. As a result, operating temperature of superalloy has been risen to 1300 °C, which helped create strong jet engines.

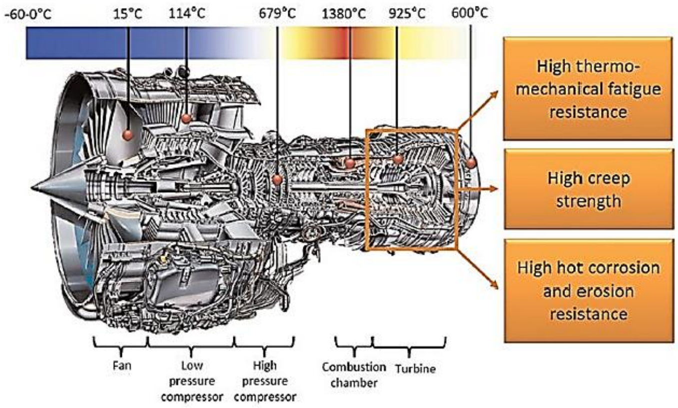


Fig. 2: Sections of Gas Turbine Engine with high temperatures [6]

However, its complex microstructure and the presence of certain alloying elements can pose challenges during welding, impacting its weldability and the mechanical properties of the resulting joints [7]. This article reviews the existing literature on the microstructure, weldability, and mechanical properties of Inconel 718 when processed using laser welding techniques.

II. MICROSTRUCTURE OF INCONEL 718

Inconel 718's microstructure is significantly influenced by its chemical composition and subsequent heat treatments [8]. Table 1 shows typical composition of IN718 superalloy.

Table 1: Typical chemical composition of IN718 (wt. %)

Element	Content in wt.%
Nickel (Ni)	50 to 55
Chromium (Cr)	17.0 to 21.0
Iron (Fe)	17
Niobium (Nb)	4.75 to 5.5
Molybdenum (Mo)	2.80 to 3.30
Cobalt (Co)	1
Titanium (Ti)	0.9
Aluminium (Al)	0.6
Silicon (Si)	0.35
Manganese (Mn)	0.35
Copper (Cu)	0.3
Carbon (C)	0.08
Phosphorous (P)	0.015
Sulphur (S)	0.015
Boron (B)	0.006

The alloy is known for its precipitation-hardened nature, with the formation of γ' and γ'' precipitates contributing significantly to its strength [9]. The presence of these precipitates, along with other phases like Laves phase, can affect weldability and mechanical properties [10, 11]. Figure 3 demonstrated the impacts of alloying elements on Inconel 718 alloy in a schematic manner.

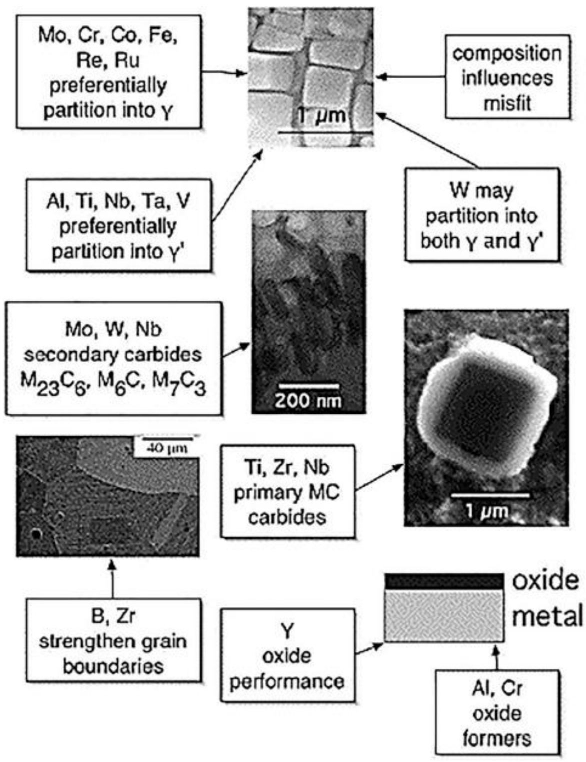


Fig. 3: Alloying element effects in nickel-based superalloys [12]

The distribution and morphology of these phases are crucial in determining the overall mechanical performance [13]. Variations in grain size, from ASTM #4 to #10, also influence the laser welding response, with finer grain sizes exhibiting better weldability [14]. The segregation of elements like Nb, Ti, and Mo within the microstructure impacts the solidus-liquidus temperatures, affecting the formation of liquid films during welding and increasing hot cracking susceptibility [15]. This is particularly true in the partially melted zone (PMZ) of the heat-affected zone (HAZ) [16]. Moreover, the initial microstructure (wrought, as-cast, or homogenized) influences the microstructure of the PMZ and therefore the weldability.

III. WELDABILITY OF INCONEL 718

The weldability of Inconel 718 is challenging due to its susceptibility to hot cracking, especially in the HAZ [17, 18, 19]. Grain boundary liquation, caused by the melting of low-melting-point phases at grain boundaries, is a significant factor contributing to hot cracking [20]. This liquation mechanism is influenced by the segregation of elements like boron, phosphorus, and carbon to grain boundaries [21]. Adding carbon can mitigate the negative effect of boron and phosphorus on weldability [22]. Pre-weld heat treatments play a crucial role in mitigating hot cracking by minimizing non-equilibrium grain boundary segregation and inhibiting grain growth [23]. Post-weld heat treatments (PWHT) can further influence the microstructure and mechanical properties, with modified cyclic solution heat treatments shown to reduce microfissures and improve mechanical properties [24]. The choice of filler wire can also affect weld quality and mechanical properties. Different welding processes, including CO2 laser welding, pulsed current gas tungsten arc welding (PCGTAW), and activated flux tungsten inert gas (A-TIG) welding [25], have shown varying effects on the weld microstructure and mechanical properties. Laser welding, specifically, can result in the formation of a sound fusion zone with minimal cracking, but HAZ microfissuring remains a concern [26, 27, 28]. The use of narrow-gap laser welding can improve the joint geometry and minimize defects in thicker Inconel 718 plates [29]. Additive manufacturing techniques like selective laser melting (SLM) provide a different approach, but the resulting microstructure and weldability of SLM-produced Inconel 718 are influenced by process parameters such as laser energy density and build orientation [30, 31, 32].

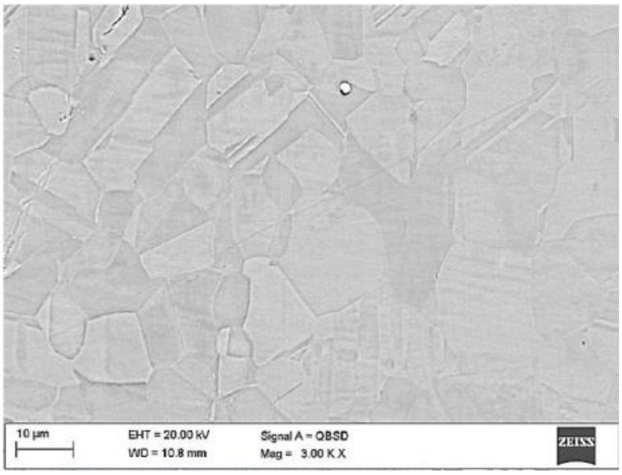
IV. MECHANICAL PROPERTIES

The mechanical properties of Inconel 718 laser welds are significantly affected by both the welding process and subsequent heat treatments [33, 34]. Tensile strength, yield strength, and impact toughness are influenced by the microstructure of the weld and HAZ. Laser welding can lead to improved tensile strength in certain conditions [35], but the impact toughness may be lower than the base metal due to the presence of secondary phases or defects [36]. The formation of Laves phase can decrease toughness [37]. Heat treatments significantly influence the mechanical properties [38, 39, 40], particularly by controlling the precipitation hardening process. The orientation dependence of mechanical properties is particularly relevant in SLM-produced Inconel 718 due to its columnar grain structure [41, 42]. High-temperature mechanical properties are also influenced by the microstructure, and high-temperature tensile strength may decrease due to the accumulation of cavities [43].

V. COMPARATIVE STUDY OF DIFFERENT WELDING PROCESSES ON IN718

A. GTAW

Gorka et al. researched the impact of TIG welding on the hardness and structure of Inconel 718 butt junctions. The austenite grains in the Inconel 718 sheets had a microscopically determined size that was limited to around 5 μm to 20 μm. Fine austenite grains were also seen in the Inconel 718 joints' heat-affected zone structure. The size of the grains γ increased from about 10 μm to about 20 μm when the welding arc linear energy was increased from 45 J/mm to 80 J/mm [44].



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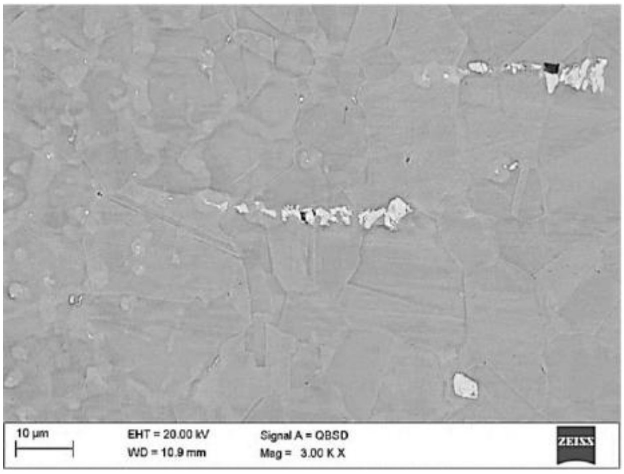

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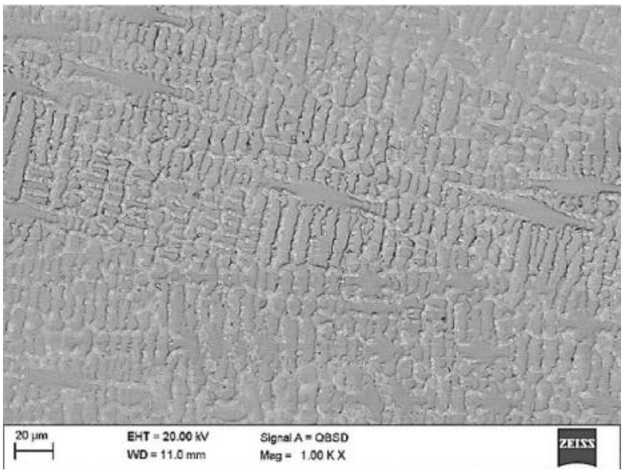

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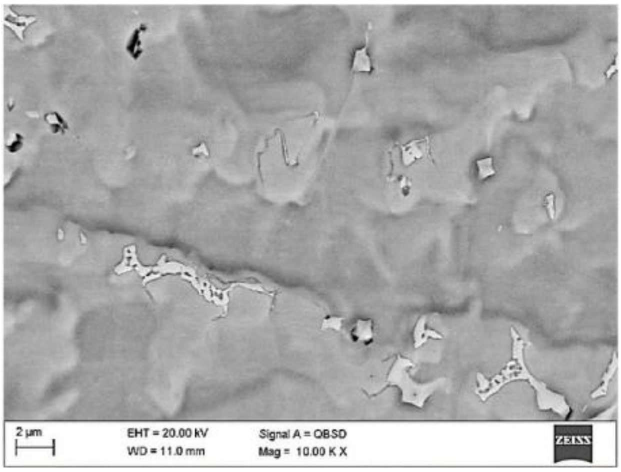
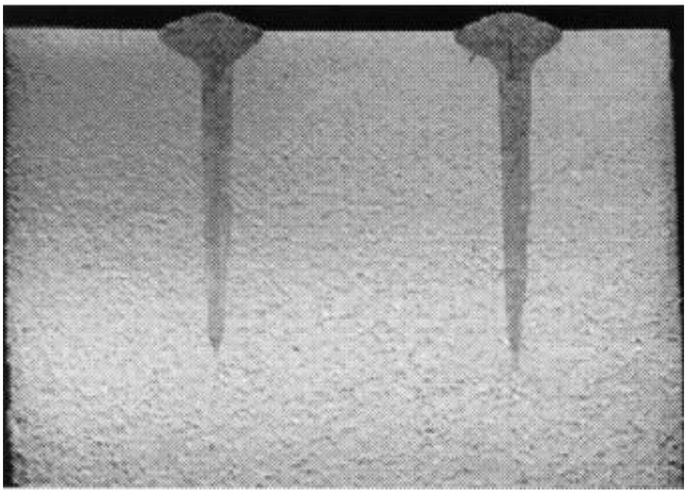


(d)

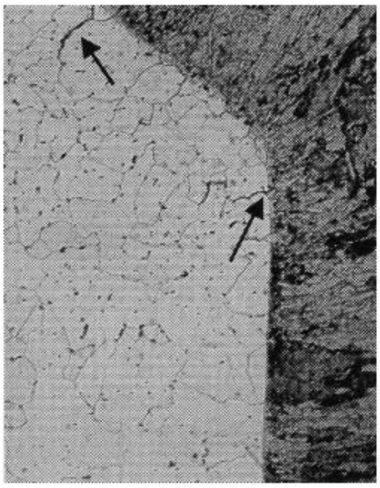
Fig. 4: Microstructure of the joint made of Inconel 718: (a) Base Material (b) HAZ (c) dendritic microstructure of the weld (d) precipitates and low-melting eutectics [44]

B. Electron beam welding (EBW)

Huang et al. studied the effects of EBW on cast alloy IN718. They compared to conventionally cast material which has an average grain size of roughly 3 mm, the micro cast material which has an average grain size of 82–93 mm, shows greater HAZ microfissuring in terms of Total Crack Length (TCL).



(a)

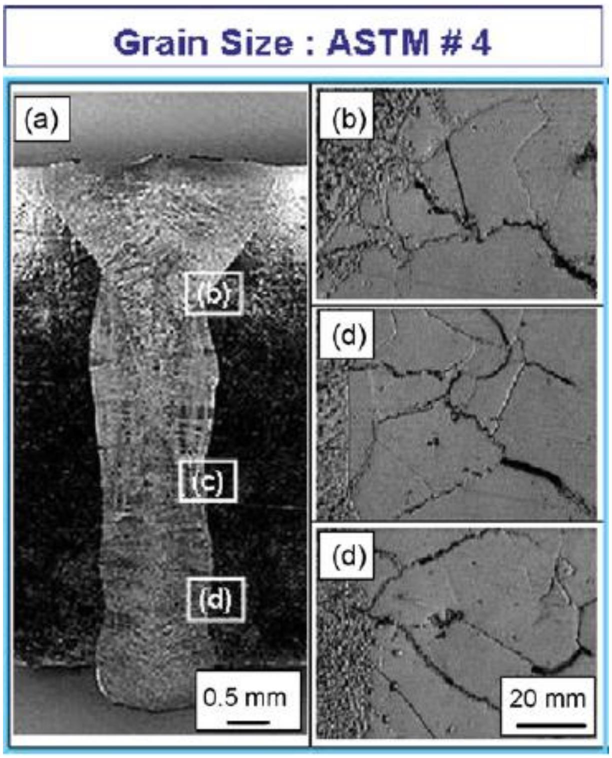


(b)

Fig.5: (a) Shape of Electron Beam Weld (5X) (b) Microfissures (arrow signs) observed in EB weld [28]

C. CO2 Laser Welding

Hong et al. studied the micro-structures and mechanical properties of IN718 welded by CO_2 laser beam welding. Before Post Welding Heat Treatment (PWHT), Micro-fissures were seen on the HAZ of large-grained Inconel 718 with ASTM #4 at a laser power of 6kW and a welding speed of 2.5 m/min, as seen in Fig. 5.



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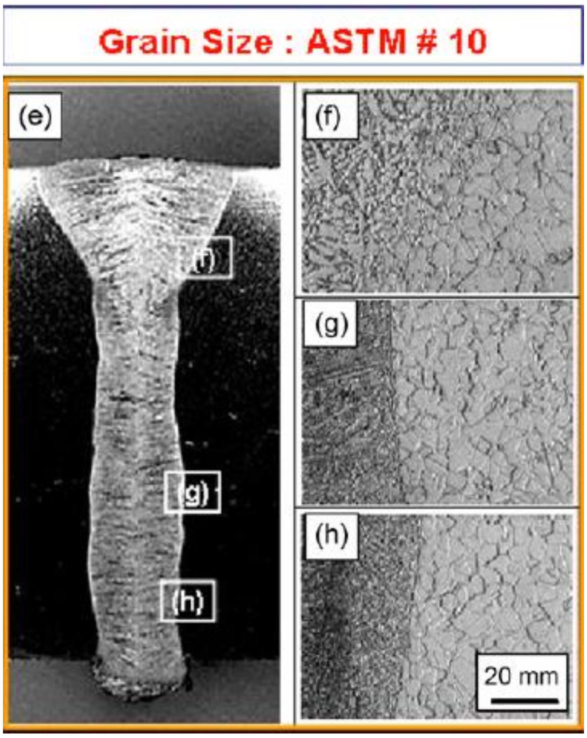

(b)

Fig. 5: Cross-section of welded specimen and Micro-structure of HAZ at 6kW, 2.5 m/min welding speed (a) Grain Size: ASTM #4 (Coarse) (b) Grain Size: ASTM #10 (Fine) [45]

Pedro et al. compared the hot cracking susceptibility of TIG and LBW on IN718 by Varestraint testing device and found that hot cracking susceptibility in LBW condition is more than that of TIG welding.

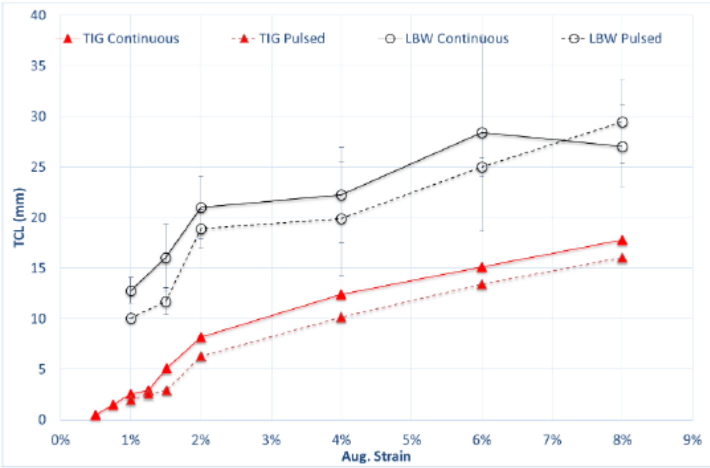

Fig. 6: TCL versus augmented strain (ε) curve resulting from the Varestraint test and showing the cracking response of wrought alloy 718 under different welding conditions [46]

D. SLM Technology

Additive manufacturing processes like SLM yield a highly refined microstructure with a uniform distribution of precipitates. Heat treatment further optimizes this structure by dissolving undesirable phases like δ and Laves phases while precipitating γ'/γ'' phases for strengthening [47, 48].

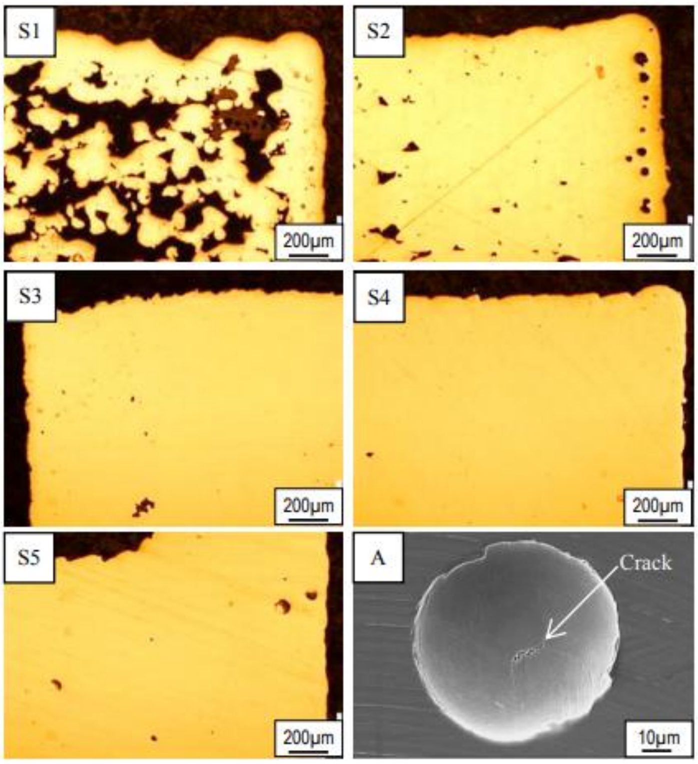

Fig. 7: An SEM picture of five typical specimens of Selective Laser Melted IN718 pore and its surface crack (A) [49]

VI. CONCLUSIONS

Laser welding of Inconel 718 offers several advantages, particularly for applications requiring precise control over the weld geometry and minimal heat input. However, careful optimization of welding parameters, pre- and post-weld heat treatments, and filler materials are crucial to mitigate the challenges of hot cracking and other metallurgical issues to achieve desirable microstructure and mechanical properties. Future research should focus on further understanding the complex interplay between welding process, microstructure, and mechanical properties to optimize laser welding parameters and achieve high-quality welds with superior mechanical performance

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A Critical Assessment of Inconel 625 Laser Welding For Technological Advancements

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ABSTRACT

A popular choice in a variety of industries, including nuclear, marine, and aerospace, Inconel 625 is a nickel-based superalloy that is well-known for its remarkable strength, resistance to corrosion, and capacity to tolerate high temperatures. Because of its accuracy and capacity to create excellent connections with minimal heat input, laser welding is a sophisticated process frequently used in the production of high-performance materials, such as super alloys. New opportunities for the effective joining of Inconel 625 have been created by developments in laser welding technology, increasing its suitability for use in crucial components. This study offers a thorough analysis of laser welding methods used on Inconel 625, a nickel-chromium superalloy renowned for its exceptional strength at high temperatures and resistance to corrosion. This study highlights the potential and constraints related to welding Inconel 625 by examining the state of laser welding technology at the moment. A number of comparisons with conventional welding techniques are used to investigate important elements such microstructural alterations, mechanical characteristics, and joint integrity. The results address possible disadvantages such as vulnerability to porosity and cracking while highlighting the benefits of laser welding, such as accuracy, lower heat input, and better weld quality. The paper concludes by suggesting areas for future research and technological advancements that could enhance the efficiency and effectiveness of laser welding for Inconel 625.

KEYWORDS
Inconel 625, Laser welding, Microstructural Integrity, heat-affected zone (HAZ), Keyhole Mode Laser Welding.

I. INTRODUCTION

The nickel-based superalloy Inconel 625 was developed as a solid solution-reinforced material. Table I displays the composition of Inconel 625.

Table1: The typical composition of Inconel 625

Element	Composition (Weight %)
Nickel (Ni)	58.0% min
Chromium (Cr)	20.0-23.0%
Molybdenum (Mo)	8.0-10.0%
Iron (Fe)	5.0% max
Niobium (Nb)	3.15-4.15%
Cobalt (Co)	1.0% max
Silicon (Si)	0.50% max
Manganese (Mn)	0.50% max
Aluminum (Al)	0.40% max
Titanium (Ti)	0.40% max
Carbon (C)	0.10% max
Phosphorus (P)	0.015% max
Sulfur (S)	0.015% max

Inconel 625 gives the alloy remarkable resistance to oxidation and corrosion in extremely hard conditions, as well as a respectable creep at high temperatures. Because of these qualities, it is ideal for demanding applications in a range of industries, including the nuclear, aerospace, chemical, petrochemical, and maritime sectors. [1, 2]. However, because of the high niobium content and exposure to harsh circumstances, advanced welding techniques are needed to ensure weld integrity and maintain the alloy's remarkable mechanical properties. Laser welding, which provides precise control over heat input and a minimal heat-affected zone (HAZ), is a potential technique for joining Inconel 625 components. [3].

The ability of the superalloy Inconel 625 to be welded using laser technology has been the subject of numerous investigations. Janicki et al. looked into using a high-power fiber laser to fuse Inconel 625 sheets without the need for additional material. The study found that this method was effective for creating butt joints. [4]. Feng et al. investigated the production of Inconel 625 coatings using laser cladding and protective metal arc welding, paying close attention to microstructure, hardness, and wear resistance at different temperatures. The study found that the laser-cladded coatings' finer microstructure improved their hardness at higher temperatures. [5]. To determine the thickness of the resulting welds and heat-affected zones, Dobrzański et al. used a high-power fiber laser to examine the changes in the surface layer of hot work tool steel treated with Inconel 625 powder [6].

Figure 1. demonstrates how the laser cladding parameter significantly affects the final overlay's quality and shape.

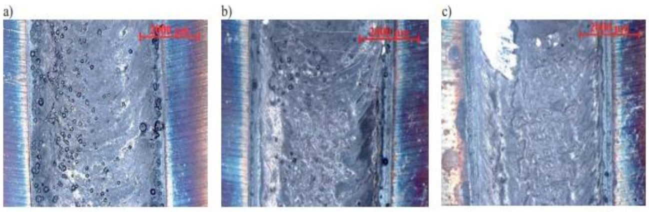
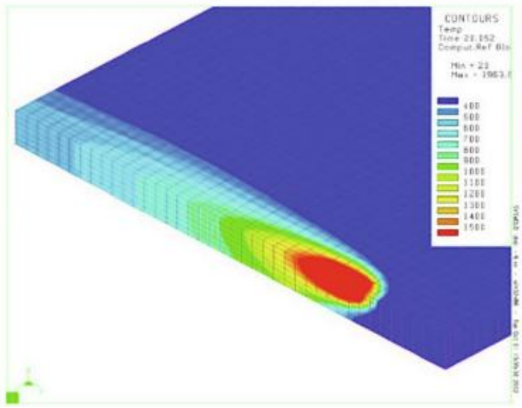


Figure 1: Shape of the laser tray of the X40CrMoV5-1 steel cladded with Inconel 625 powder, laser power: a) 2 kW, b) 2.5 kW, c) 3.0 kW [6]

In a simulation carried out by Thejasree et al. using SYSWELD software, flat sheets of Inconel 625 alloy joints measuring 70 mm in length, 50 mm in width, and 1.5 mm in thickness were selected and connected as butt joints. Figures 2 and 3 show the mesh model and the weld fusion zone that SYSWELD created for the welding that needs to be done. Little meshes are required to predict the temperature distribution in the weld zone since there is very little heat-affected area. [7].

Figures 2: Mesh Model[7]



Figures 3: Weld fusion zone[7]

Ahmad et al. effectively butt-welded Inconel 625 and duplex stainless steel using an Ytterbium fiber laser; the tensile strength of the joints was influenced by the various heat inputs. [8].

Using Gleeble thermal simulations, Liang et al. investigated how welding heat affected the mechanical characteristics and microstructure of Inconel 625 alloys produced by selective laser melting. [9]. It was demonstrated that simulated welding heat negatively impacted the alloys' mechanical characteristics, especially at peak temperatures of 1350 °C. Taken together, these studies show how valuable laser welding technology is for producing and evaluating Inconel 625 alloys, coatings, and joints.

A. Traditional welding methods

Inconel 625 is joined using a variety of conventional welding techniques, each with unique benefits and drawbacks. Shielded Metal Arc Welding (SMAW), Gas Metal Arc Welding (GMAW), and Gas Tungsten Arc Welding (GTAW) are the most often used methods. These approaches do have drawbacks, though. Heat-affected zone (HAZ) cracking is frequently caused by GTAW and related procedures, especially in cast alloys with high (Al + Ti) contents more than 3-4%. [10]. Although vacuum brazing is an option, it is mostly only used on low-stress parts. [11].

i. **Gas Tungsten Arc Welding (GTAW) :**

Because GTAW, sometimes referred to as TIG welding, can create high-quality welds with few flaws, it is frequently used to fuse Inconel 625. This technique makes it possible to precisely regulate the heat input, which is essential for preserving the alloy's integrity. According to research by Dobrzański et al., GTAW can successfully fuse Inconel 625 to other materials, like cast steel, improving the corrosion resistance of parts like diesel engine piston crowns. [12,13].

But in order to get the best outcomes, the process is somewhat slow and needs competent operators.

ii. **Gas Metal Arc Welding (GMAW) :**

Another common technique for welding Inconel 625 is GMAW, especially for applications that call for high deposition rates. According to research, GMAW can provide weld overlays with consistent microstructures, which are necessary to preserve the weld's mechanical qualities. [14,15]. Nevertheless, the technique may increase the amount of heat applied to the weld region, raising the possibility of distortion and flaws [16,17].

iii. **Shielded Metal Arc Welding (SMAW) :**

For Inconel 625, SMAW is a flexible welding method that works well, particularly in field settings [18]. For this alloy, it is less frequently employed than GTAW and GMAW, but when the right filler materials are chosen, it can still yield good results [19]. Controlling the heat input and avoiding electrode coating contamination are the two mains challenges with SMAW [20]

B. Challenges in welding Inconel 625

Even while conventional welding techniques are effective, there are still a number of difficulties when welding Inconel 625. These difficulties include the requirement for exact welding parameter control, microstructural alterations, and vulnerability to heat cracking [21,22].

i. **Susceptibility to Cracking:**

Inconel 625 is prone to hot cracking during the welding process, particularly in the heat-affected zone (HAZ) [23]. The presence of alloying elements such as niobium and molybdenum can lead to segregation and the formation of brittle phases, which compromise the integrity of the weld [24]. Studies have shown that optimizing welding parameters, such as heat input and cooling rates, can mitigate this issue [25].

ii. **Microstructural Changes:**

Welding can induce significant microstructural changes in Inconel 625, affecting its mechanical properties. For instance, the formation of carbides and other precipitates during the welding process can lead to reduced creep resistance and strength [26]. Research has demonstrated that post-weld heat treatment can help restore some of the alloy's desirable properties by dissolving detrimental phases [27].

iii. **Control of Welding Parameters:**

Achieving optimal weld quality in Inconel 625 requires precise control of various welding parameters, including current, voltage, and travel speed. Variations in these parameters can lead to inconsistent weld bead geometry and mechanical properties [28]. Advanced techniques such as Response Surface Methodology (RSM) and Grey Relational Analysis have been employed to optimize these parameters for better weld quality [29].

These limitations underscore the need for a superior welding technique that minimizes HAZ formation and ensures high-quality welds.

C. Modern welding techniques

i. **Laser Welding Techniques for Inconel 625**

Laser welding offers several advantages over conventional methods. The focused energy of the laser beam allows for precise control of the heat input, resulting in a narrower HAZ and reduced distortion [30]. Different laser types have been explored, including Nd:YAG and ytterbium fiber lasers [31]. Studies have investigated the influence of laser parameters, such as laser power (LP), spot size (SS), and welding speed (WS), on weld strength (WST), microhardness, and microstructure [32,33]. Response surface methodology (RSM) and analysis of variance (ANOVA) have been employed to optimize these parameters for achieving desired weld characteristics [34].

Laser welding is also being explored for joining Inconel 625 with dissimilar materials, such as duplex stainless steel SAF 2205. These studies have examined the microstructure, composition, and mechanical properties of the resulting weld joints, focusing on minimizing interfacial reactions and ensuring adequate joint strength [35,36].

ii. Keyhole Mode Laser Welding:

Keyhole mode laser welding is a prevalent technique for joining Inconel 625, characterized by the formation of a deep, narrow keyhole-shaped cavity in the weld pool [37]. This approach allows for deep penetration and high welding speeds, but necessitates careful control to avoid defects such as porosity [38]. Computational models based on Gaussian optics and emission theory are being developed to predict the thermal history within the weld and HAZ, enhancing process understanding and control [39]. Numerical simulations, coupled with experimental validation, are vital in optimizing keyhole welding parameters [40].

iii. Selective Laser Melting (SLM) and Subsequent Laser Welding :

Inconel 625 components manufactured via SLM offer intricate geometries but can be challenging to join. Laser welding is investigated as an effective method to join SLM-produced Inconel 625 components [41]. The microstructure of the weld zone in these cases often exhibits columnar grains, which demonstrate enhanced tensile fracture resistance and improved fatigue and creep-fatigue properties compared to the equiaxed grains of the base SLM material [42]. However, challenges persist, including potential pore formation during welding of SLM-manufactured tubes.

II. WELDING ANALYSIS

A. Microstructural analysis and mechanical properties:

Microstructural studies of laser-welded Inconel 625 reveal various features depending on the welding parameters. Grain coarsening can occur in the HAZ [43] and segregation of elements like Nb and Mo can result in the formation of Laves phases and intermetallic precipitates, such as δ and γ” phases. These phases can affect mechanical properties, with Laves phase formation potentially increasing microhardness [44]. Tensile testing has demonstrated that laser-welded joints can achieve strengths comparable to the base material, while impact toughness can be affected by the formation of Mo-rich phases [45]. The formation of Cr, Mo and Ni carbides at the weld joint interface is also noted [46]. Heat input plays a significant role in determining microstructure, porosity, bead shape, and grain size. Lower heat inputs generally lead to finer grain sizes and reduced porosity. Post-weld heat treatment can slightly alter the microstructure in the welded area and HAZ [47].

B. Comparative Analysis

i) Weld Quality and Strength:

When Inconel 625 is laser-welded as opposed to conventionally, the weld quality and strength are usually better. Because of the laser's concentrated energy, the weld pool can be precisely controlled, resulting in fewer inclusions and porosity. Laser welding's quick cooling rates help create a finer microstructure, which frequently leads to improved mechanical qualities including increased fatigue resistance and tensile strength. The integrity of the weld may be jeopardized by conventional techniques like TIG and MIG welding, which may result in greater heat-affected zones (HAZ), increased deformation, and residual strains.

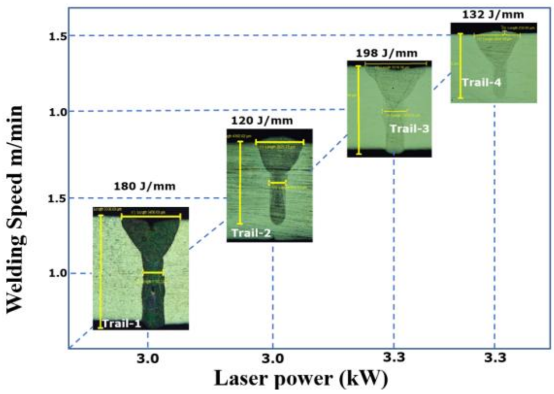
ii) Heat Affected Zone (HAZ):

In general, laser welding produces a narrower HAZ than conventional welding methods. Because of the laser's concentrated heat input, the thermal gradient is reduced and the amount of thermal damage to the surrounding material is lessened. Because it maintains the mechanical qualities of the base material, a smaller HAZ helps to ensure that the weld region remains strong and resistant to corrosion. The welded connection is more likely to break under stress when using traditional procedures because they frequently produce a wider HAZ, which can result in unfavorable changes in microstructure and mechanical properties.

iii) Speed and Efficiency:

When compared to conventional techniques, laser welding is known for its great speed and efficiency, which drastically cuts down on the amount of time needed to complete welds. Faster processing times are made possible by the capacity to accomplish deep penetration in a single pass, which is especially advantageous in high-volume manufacturing settings. Furthermore, laser welding systems' automated features improve consistency and productivity. Even while they work well, traditional welding techniques frequently call for more passes and longer setup times, which can slow down the manufacturing process as a whole. Vemanaboina et al. noted the effects of laser power and welding speed on the Inconel
625 laser beam.

The relationship was depicted in the figure 4



Figures 4: Macrographs of Inconel 625 laser beam welded joints as a function of process parameters (laser power and welding speed) [48]

iv) Cost Considerations:

The long-term financial advantages of laser welding technology frequently exceed the original costs, even though the initial expenditure may be greater than those of conventional welding techniques. Lower labor expenses and less material waste may result from laser welding's greater speed and efficiency. Additionally, laser welding produces high-quality welds that can reduce the need for rework and repairs, which further reduces costs. Due to lengthier processing periods and possible quality problems, traditional welding techniques may be less expensive initially but may result in greater operating expenses over time.

III. SUCCESSFUL APPLICATIONS OF TRADITIONAL WELDING ON INCONEL 625

Traditional welding methods, such as TIG and MIG welding, have also found successful applications in working with Inconel 625, particularly in environments where cost-effectiveness and accessibility are paramount. TIG welding, known for its ability to produce high-quality welds with excellent control over the heat input, is frequently used in the fabrication of Inconel 625 components in the chemical processing and aerospace industries. This method is particularly advantageous for thin-walled sections, where precision is essential to avoid warping and ensure structural integrity. MIG welding has been effectively employed in the construction of large structures and components made from Inconel 625, such as pressure vessels and piping systems. The speed and efficiency of MIG welding make it a preferred choice for projects requiring high throughput. Additionally, the versatility of MIG welding allows for the use of various filler materials, which can be tailored to meet specific mechanical property requirements. In the context of dissimilar metal welding, traditional methods have been successfully applied to join Inconel 625 with other materials, such as carbon steels and stainless steels. These applications are particularly relevant in industries like power generation and marine engineering, where the ability to join different alloys is crucial for the performance and longevity of components. Overall, while traditional welding methods may not offer the same level of precision as laser welding, they remain a viable option for many applications involving Inconel 625, particularly where cost and speed are critical factors.

IV. CONCLUSION AND FUTURE DIRECTIONS

Laser welding has shown significant promise as a superior technique for joining Inconel 625 components. This review highlights various laser sources and welding methodologies, focusing on process optimization, microstructural evolution, and mechanical properties. Advanced characterization techniques and numerical modeling are proving invaluable in understanding the complex interactions between processing parameters, microstructure, and performance. Future research should focus on:

- Further optimization of laser welding parameters for specific applications, minimizing defects, and maximizing joint performance.
- Development of advanced process monitoring and control strategies for improved reproducibility and quality assurance.
- Exploration of novel laser sources and welding techniques to enhance efficiency and reduce environmental impact.
- Comprehensive life cycle assessments to minimize the environmental footprint of Inconel 625 laser welding.

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A Comprehensive Review of Traditional Welding and Laser Beam Welding Techniques for Inconel 800

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ABSTRACT

This study focuses on a comprehensive review of traditional welding and laser welding techniques for Inconel 800. A direct comparison of laser beam welding and traditional welding for Inconel 800 reveals a number of significant differences. LBW offers significant advantages in terms of welding speed and reduced heat-affected zones (HAZ) width, leading to better control over the microstructure and improved mechanical properties. The high precision and automation capabilities of LBW are particularly advantageous in high-volume manufacturing. However, traditional methods might be more cost-effective for low-volume applications or situations where complex joint geometries are difficult to manage with a laser. Inconel 800, an iron-nickel-chromium based super alloy also known for high-temperature strength and corrosion resistance, is used in extreme conditions. The choice between LBW and traditional techniques is dependent on specific application requirements and constraints, weighing the benefits of speed and precision against cost and potential process limitations. Based on the needs of our industrial application, laser beam welding is a more practical way to create high quality joints than other traditional welding techniques.

Keywords: Laser beam welding (LBW), Inconel 800 Alloy, HAZ, Microstructure, Mechanical Properties.

I. INTRODUCTION

Inconel 800, a nickel-chromium-iron alloy, finds extensive use in high-temperature and corrosive environments due to its exceptional properties[1]. Joining Inconel 800 components efficiently and reliably is crucial for numerous applications. Traditional welding methods, such as Gas Tungsten Arc Welding (GTAW) and Gas Metal Arc Welding (GMAW), have been employed, but they often face limitations in terms of speed, penetration depth, and heat-affected zone (HAZ) control [2]. Laser beam welding (LBW), a high-energy density process [3], offers a potential solution to these challenges. This paper compares traditional welding and LBW techniques for Inconel 800, examining their respective advantages and disadvantages concerning weld quality, efficiency, and metallurgical characteristics.

II. METHODS AND MATERIAL

A. Traditional Welding of Inconel 800

Traditional methods like GTAW and GMAW are widely used for joining Inconel 800 [4]. These processes utilize an electric arc to melt the base metal, creating a weld pool. However, the relatively low power density of these techniques can lead to wider HAZs, potentially affecting the microstructure and mechanical properties of the weld [4,5]. The slower welding speeds compared to LBW also impact productivity. For instance, highlights that GTAW, GMAW, and GMA-tandem welding, while common in pipeline manufacturing, suffer from limitations in welding speed and penetration depth [6]. Furthermore, the challenges posed by the weldability of certain Inconel alloys, particularly those prone to cracking and microstructural segregation in the HAZ, are well-known [7].

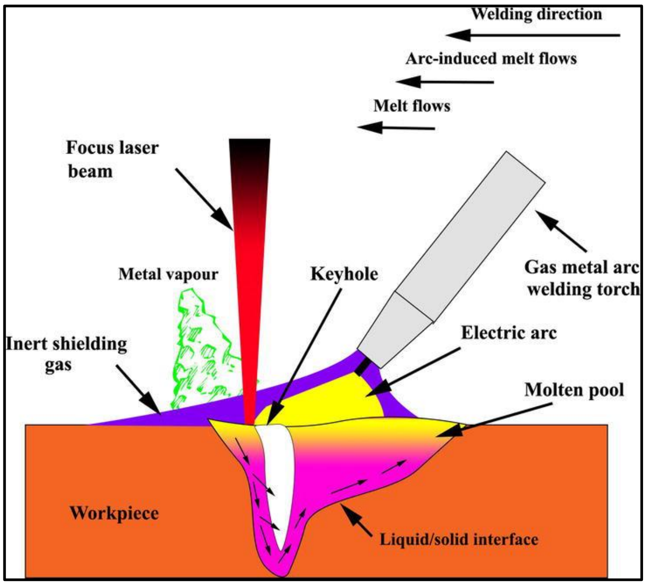

Figure 1: Hybrid laser GMAW welding process [8].

B. Laser Beam Welding (LBW) of Inconel 800

LBW utilizes a highly focused laser beam to melt and fuse the Inconel 800 material [9]. The high power density allows for deep penetration and narrow welds, resulting in smaller HAZs and improved joint efficiency [10,11]. The process's precision and speed are significant advantages over traditional methods [12]. Studies such as demonstrate the effect of LBW parameters (e.g., scan speed) on the microstructure and mechanical properties of Inconel 800, showing that variations in cooling rate can impact the formation of phases like Laves phases and affect the joint's ductility [13,14]. Moreover, LBW's flexibility in automation and adaptability to different geometries make it attractive for various applications [15,16]. The ability to achieve full penetration keyhole welds, even in thicker Inconel 800 sheets, as illustrated in underscores the potential of this technique [17]. Research in further showcases the enhanced penetration depth and process stability achieved using LBW under vacuum conditions [18]. Different LBW configurations such as pulsed wave lasers and continuous wave lasers are also explored and compared in literature demonstrating varying weld outcomes [3][9].

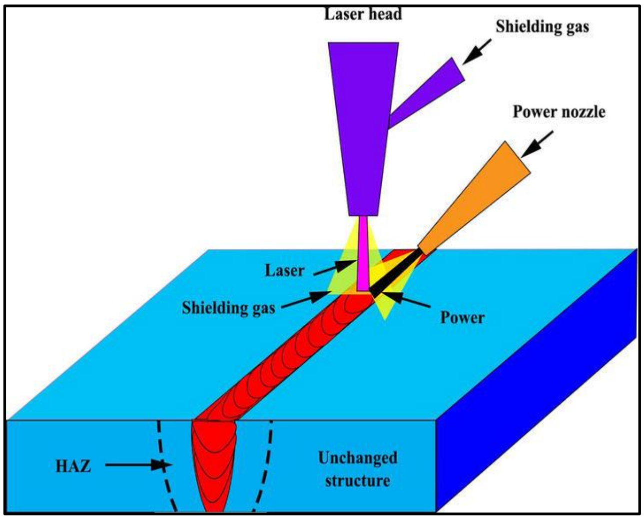

Figure 2: The key components of laser welding procedure [8].

III. RESULTS AND DISCUSSION

The main focuses on this study to comparison between traditional welding and laser welding techniques for Inconel 800 on heat affected zone, mechanical Properties, microstructural considerations, precision and Weld Quality, speed and cost of welding and applications of welding.

A. Heat Input and Heat-Affected Zone (HAZ)

i) Laser Welding:

It produces a highly concentrated heat source, resulting in a smaller HAZ. This minimizes thermal stress, distortion, and grain coarsening, which can improve mechanical properties like tensile strength and fatigue resistance [13] [19].

ii) Traditional Welding:

Involves higher heat input, leading to a larger HAZ. This can cause more significant thermal stresses, grain growth, and potential weakening of the weld joint [4] [20].

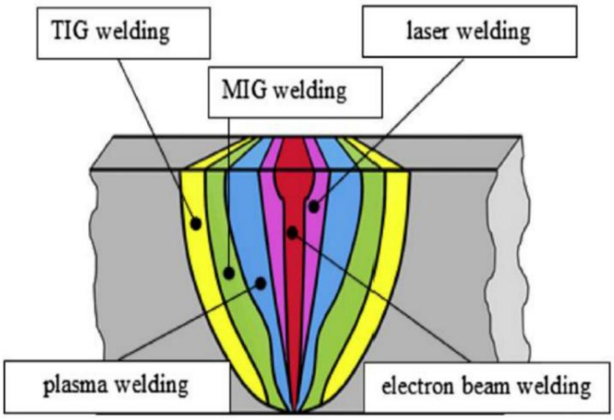

Figure 3: Schematic view of the weld-width with different welding techniques[21].

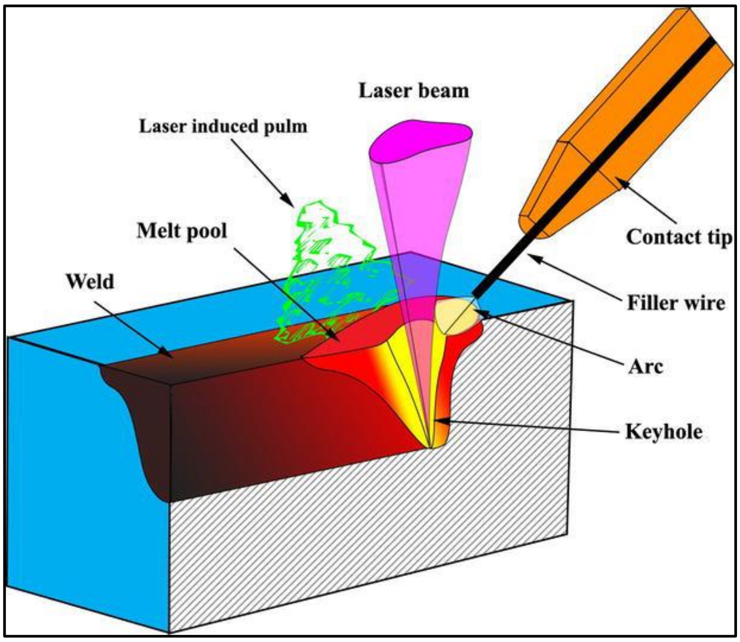

Figure 4: The keyhole formation and laser welding using keyhole mode [8].

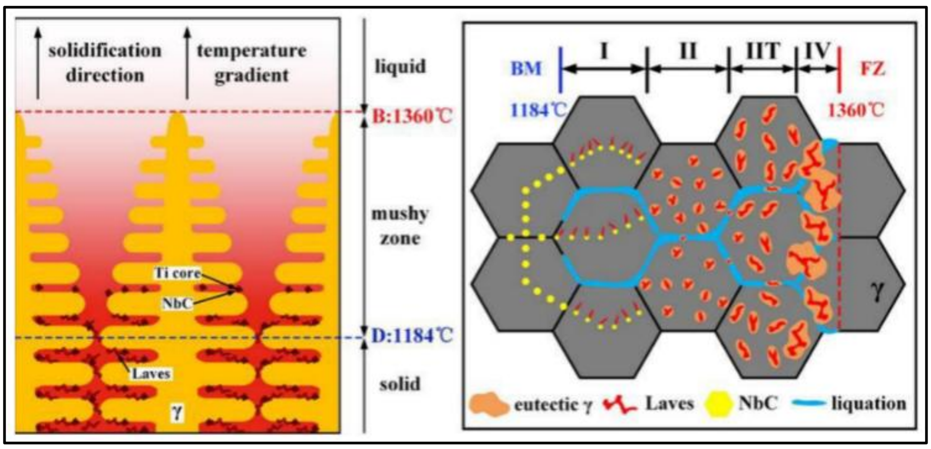

Figure 5: Representation of the solidification processes and constituents formation in FZ (equivalent to melted zone MZ) and HAZ of GH909 Ni-based super alloy [22].

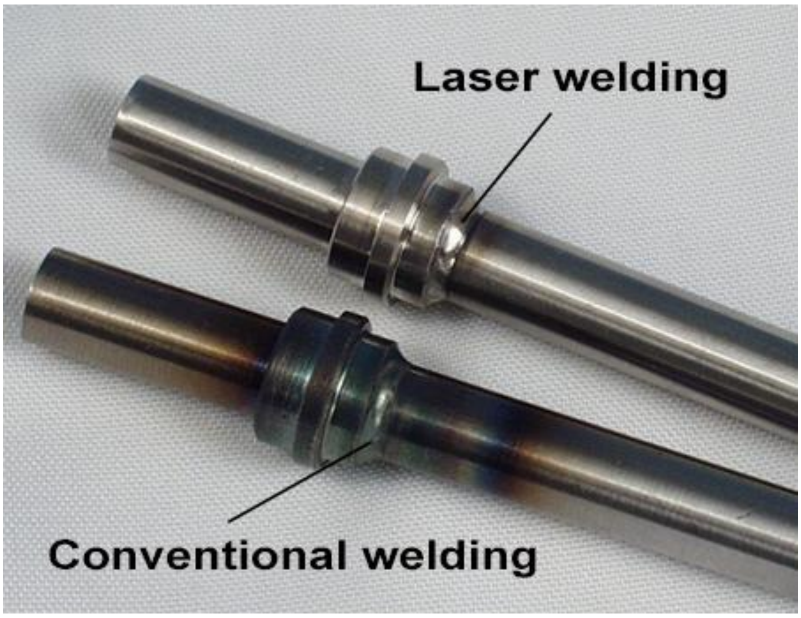

Figure 6: Heat-affected zones Laser welding vs. conventional welding [23]

B. Mechanical Properties:

i) Laser Welding: Optimized parameters (e.g., welding speed, laser power) can enhance the tensile strength and fatigue life of Inconel 800 welds by refining microstructure and reducing grain size in the fusion zone [13] [24].

ii) Traditional Welding: Mechanical properties are often lower in the fusion zone compared to the base metal due to coarser grains and residual stresses from higher heat input [25] [26]

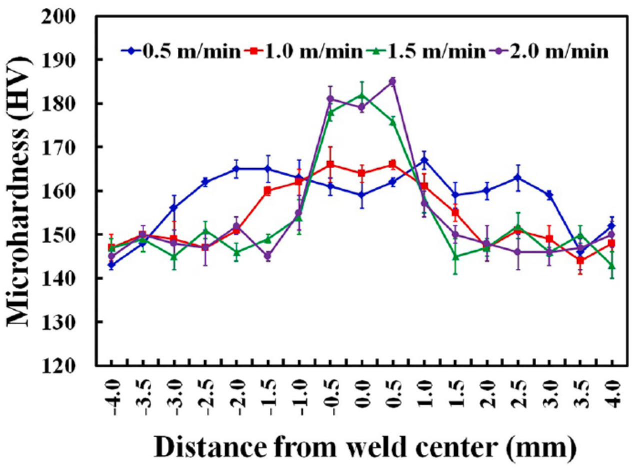

Figure 7: Variation of microhardness as a function of scanning speed [13].

C. Microstructural Considerations

i) Laser Welding:

Palanivel et al. examined the microstructural evolution of Inconel 800 alloy during laser welding, revealing significant phase transformations due to the high cooling rates. The study indicated that the mechanical properties were closely linked to the microstructural characteristics, with laser welding providing a more favourable microstructure compared to traditional methods [13].

ii) Traditional welding:

The microstructure of welded joints plays a crucial role in determining their mechanical properties. Traditional welding methods can lead to the formation of undesirable phases and grain growth, which can compromise the strength and ductility of the welds. In contrast, laser welding's rapid cooling rates can result in finer microstructures, which are often associated with improved mechanical properties [25] [26].

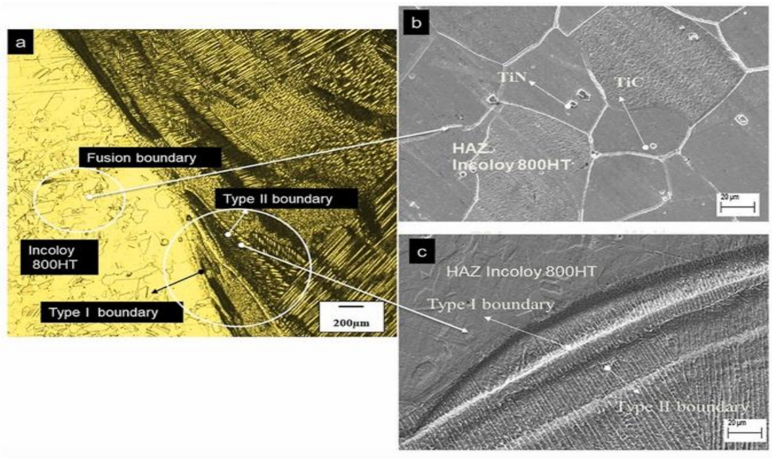

Figure 8: Incoloy side fusion boundary [13]

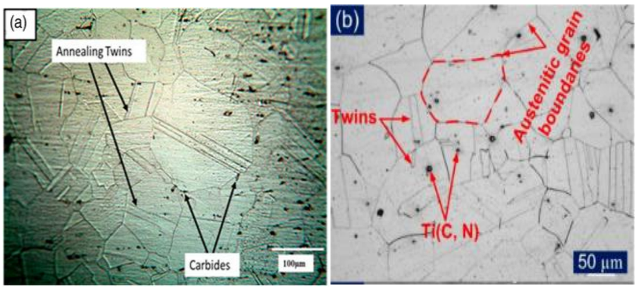

Figure 9: (a) Microstructure of base alloy 800 (b) Incoloy 800HT base metal optical microstructure [26]

D. Precision and Weld Quality

i) Laser Welding: Offers high precision with deep penetration and narrow welds, making it ideal for intricate or thin materials. It also reduces defects such as porosity and cracking when parameters are optimized [27] [28].

ii) Traditional Welding: While versatile, it generally produces wider welds and may have higher susceptibility to defects like porosity and inclusions due to less controlled heat application [29] [30] [31].

E. Speed and Cost:

i) Laser Welding: Faster processing speeds lead to higher productivity but require significant initial investment in equipment [13] [32] [33].

ii) Traditional Welding: Slower but more cost-effective for lower-budget applications due to simpler equipment requirements [34] [35] [36].

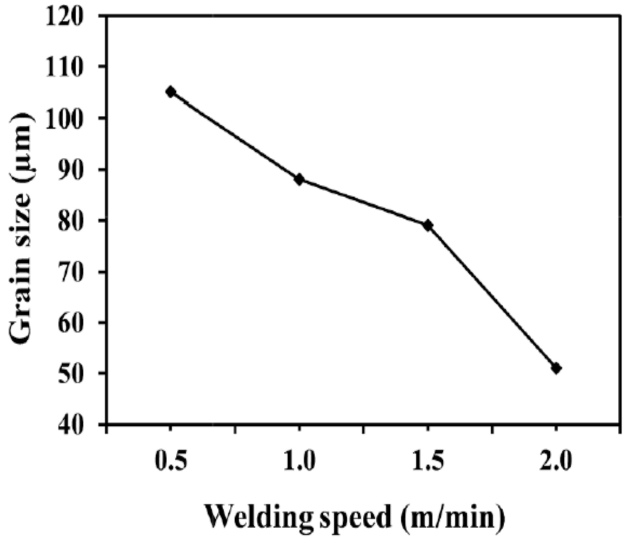

Figure 10: Variation of grain size as a function of scanning speed [13].

E. Applications:

i) Laser Welding: Preferred for high-precision industries like aerospace and nuclear applications where superior mechanical properties are critical [37] [38].

III.6.B Traditional Welding: Commonly used in general fabrication where precision is less critical [39] [40].

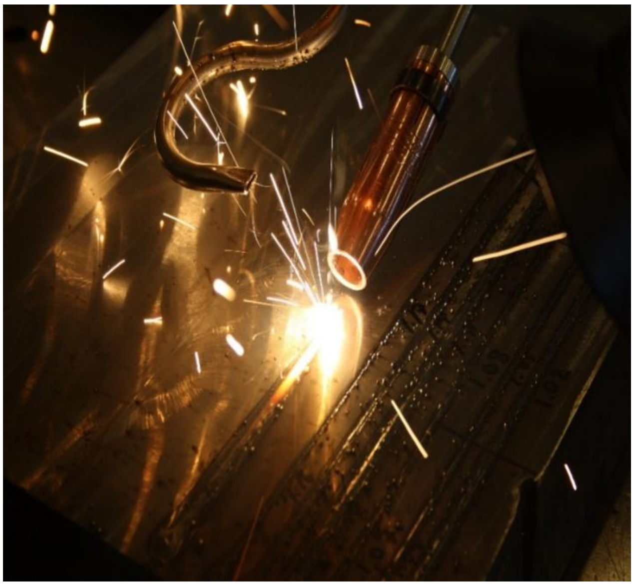

Figure 11: Application of laser welding [41]

TABLE I: List of Different Welding Techniques and their Capabilities.[42]

Welding Technology	Weld Speed	Weld Precision	Thickness Limitation	Compatible Materials	Applications	Equipment Cost
Laser	Very Fast	Very High	0.25" (6 mm)	Metals: Carbon Steel, Stainless Steel, Copper, Aluminium, Magnesium, Nickel, and Titanium Non-	Automotive Medical Aerospace Electronics Jewellery Tool and Die	Low-High

				Metals: Ceramics, PP, PS, PC, ABS, PMMA, PET, and PBT	Heavy Machinery	
TIG	Medium	Medium	0.10" (2.5 mm)	Steel, Stainless Steel, Aluminium, Nickel, Magnesium, Copper, and Gold	Pipeline Aviation Aerospace	Low
MIG	Fast	Medium	0.50" (12.7 mm)	Aluminium, Carbon Steel, Stainless Steel etc.	Heavy Machinery Construction Pipeline Automotive	Low

IV. CONCLUSION

This comprehensive review has highlighted the significant differences between traditional welding and laser beam welding for Inconel 800, with particular emphasis on their respective impacts on microstructure, mechanical properties, and overall joint performance. While traditional methods like GTAW and GMAW continue to serve important roles in certain applications, LBW offers distinct advantages in terms of reduced heat input, minimized HAZ, refined microstructure, and enhanced mechanical properties.

The selection of the optimal welding technique for Inconel 800 should be based on a thorough evaluation of specific application requirements, considering factors such as joint design, material thickness, performance criteria, and economic constraints. For applications demanding superior mechanical properties, minimal distortion, and high production efficiency, laser beam welding represents an increasingly attractive option despite its higher initial investment costs.

Future research in this field should focus on further optimization of laser welding parameters for Inconel 800, development of advanced hybrid techniques, and comprehensive economic analyses to quantify the cost-benefit relationships across different application scenarios. As industrial demands for high-performance materials and joining solutions continue to evolve, the ongoing advancement of welding technologies for Inconel 800 will remain a critical area of research in materials engineering and development.

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Advanced Powertrain Technologies

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ABSTRACT

With the increasing demand for fuel efficiency and reduction in emissions, the automotive industry has witnessed rapid developments in advanced powertrain technologies. This paper explores key innovations including hybrid systems, electric drivetrains, hydrogen fuel cells, and other emerging solutions. The integration of these technologies not only contributes to sustainable mobility but also significantly impacts vehicle performance, cost, and consumer acceptance. Through a comprehensive review, this study highlights the current trends, challenges, and prospects of advanced powertrain systems.

Keywords: Advanced Powertrain, Hybrid Electric Vehicle (HEV), Fuel Cell Electric Vehicle (FCEV), Electrification, Emissions

I. INTRODUCTION

The automotive sector is undergoing a transformative shift driven by environmental regulations, technological innovations, and consumer demand for cleaner transportation. Traditional internal combustion engines (ICEs), though still dominant, face increasing scrutiny due to their contribution to greenhouse gas emissions. Consequently, the industry has turned its focus toward advanced powertrain technologies that promise enhanced performance, improved fuel efficiency, and lower emissions.

This paper investigates the fundamental advancements in powertrain technologies, particularly emphasizing hybrid systems, full electrification, and hydrogen-based alternatives

II. ADVANCED POWERTRAIN TECHNOLOGIES

Advanced powertrain technologies refer to next-generation propulsion systems that aim to improve vehicle efficiency, reduce emissions, and enhance performance. These include hybrid, electric, and alternative fuel powertrains. Key features often include:

a) Electrification (full or partial)
b) Energy recovery (e.g., regenerative braking)
c) Intelligent energy management systems
d) Lightweight and compact components

A. Hybrid Electric Vehicle (HEV)

An HEV combines a traditional internal combustion engine (ICE) with an electric motor and battery.

a) Operation Modes: Can run on engine, electric motor, or both.
b) Energy Recovery: Regenerative braking helps charge the battery.
c) Efficiency: Better than ICE-only vehicles, especially in urban stop-and-go traffic.
d) Examples:Toyota Prius, Honda Accord Hybrid

Pros:

a. No need to plug in (self-charging)
b. Good fuel economy
c. Lower emissions than ICE

Cons:

a. Still uses fossil fuels
b. Limited electric-only range

B. Battery Electric Vehicle (Bev)

A BEV is a fully electric vehicle with no ICE. It uses only an electric motor powered by a high-capacity battery.

a. Zero tailpipe emissions
b. Must be plugged into a charger
c. Range depends on battery capacity (typically 150–400 miles)
d. Examples: Tesla Model 3, Nissan Leaf, Hyundai Ioniq 5

Pros:

a. No fuel cost, lower running cost
b. Quiet, smooth operation
c. Zero local emissions

a) Cons:

a. Limited charging infrastructure (in some areas)
b. Longer refueling (charging) time
c. Battery cost and degradation

C. Fuel Cell Electric Vehicle (FCEV)

a) FCEVs use hydrogen fuel cells to generate electricity onboard, which then powers an electric motor.
b) The only by-product is water vapor
c) Hydrogen is stored in high-pressure tanks
d) Examples: Toyota Mirai, Hyundai NEXO

Pros:

a. Zero emissions
b. Fast refueling (3–5 minutes)
c. Longer range than most BEVs

Cons:

a. Expensive technology and production
b. Limited hydrogen refueling stations
c. Hydrogen production may not be entirely clean

D. Internal Combustion

The ICE is a conventional engine that burns gasoline or diesel to generate mechanical power.

a. Widely used for over a century
b. Powers most vehicles globally

Pros:

a. Mature, reliable technology
b. Extensive refueling infrastructure

Cons:

a. Low efficiency (~25–30%)
b. High CO_2 and NOx emissions
c. Dependent on fossil fuels

E. Electrification

Electrification refers to the integration of electric power in vehicle systems, ranging from:

a. Mild hybrids (12V/48V systems)
b. Full hybrids (HEVs)
c. Plug-in hybrids (PHEVs)
d. Battery electric (BEVs)
e. Fuel cell electric vehicles (FCEVs)

Benefits:

a. Lower fuel consumption
b. Reduced emissions
c. Better performance (torque and responsive)

F. Evolution of Powertrains

The journey of powertrain evolution has followed a trajectory from mechanical complexity to electronic sophistication. Early engines focused purely on mechanical output, whereas today's powertrains integrate software, sensors, and multiple energy sources.

i) Internal Combustion Engine (ICE)

Despite criticisms, ICEs have evolved through technologies such as turbocharging, direct injection, and variable valve timing. Improvements continue to reduce fuel consumption and meet stringent emission norms (e.g., Euro 6, BS VI).

ii) Hybrid Powertrains : Hybrid vehicles use a combination of ICE and electric motors. Variants include mild hybrids (MHEV), full hybrids (HEV), and plug-in hybrids (PHEV), each offering varying degrees of electric assistance.

iii) Electrified Drivetrains : Battery Electric Vehicles (BEVs) eliminate tailpipe emissions and offer high torque efficiency. Challenges remain in terms of battery range, cost, and charging infrastructure.

iv) Fuel Cell Electric Vehicles (FCEV) : FCEVs use hydrogen to generate electricity via electrochemical processes. They offer fast refueling and long range, although infrastructure and hydrogen production remain bottlenecks.

G. Key Components and Technologies

i) Electric Motors and Controllers: Modern powertrains use high-efficiency AC motors (e.g., PMSM, induction motors) controlled via sophisticated inverters. Software algorithms optimize torque, speed, and energy recovery (regenerative braking).

ii) Battery Systems: Lithium-ion batteries dominate, though solid-state and sodium-ion chemistries are gaining traction. Key concerns include energy density, thermal management, and lifecycle.

iii) Transmission Systems:

Advanced powertrains often use single-speed or multi-speed electric transmissions, continuously variable transmissions (CVT), or e-CVTs that combine mechanical and electrical drive seamlessly.

Power Electronics Inverters, DC-DC converters, and onboard chargers play crucial roles in energy flow and conversion. SiC and GaN semiconductors enhance efficiency and reduce

H. Integration and Control Strategies

Effective integration of ICE, electric motors, batteries, and control units is vital. Energy management strategies are implemented via vehicle control units (VCUs) to determine optimal operating modes (electric-only, hybrid, regeneration).

Model Predictive Control (MPC) and Artificial Intelligence (AI) approaches are emerging in managing these complex systems, enhancing responsiveness and overall efficiency.

Regulatory pressures are central to the shift toward clean technologies. Governments across the globe have set targets for CO_2 reduction, NOx limitations, and zero-emission vehicle mandates.

Powertrain innovations must balance performance with environmental compliance. Lifecycle assessments (LCA) and well-to-wheel (WTW) analyses are becoming standard in evaluating true emissions impact.

III. CHALLENGES AND FUTURE OF ADVANCED POWERTRAINS

The development and deployment of advanced powertrains face several challenges, ranging from technological and economic barriers to societal acceptance. However, the future holds promising advancements that could overcome these obstacles and transform the automotive landscape.

A. Key Challenges

i) Battery Technology and Energy Density:

One of the primary challenges for electric and hybrid powertrains is improving battery energy density. While current batteries provide sufficient range for many electric vehicles (EVs), long-range applications, especially in commercial transport, require further.

ii) Charging Infrastructure for EVs and PHEVs:

The development of a robust and widespread charging infrastructure remains a significant challenge. Although public and private investments in charging stations are increasing, the lack of fast-charging stations in many regions and the variability in charging standards can deter consumers from adopting electric and plug-in hybrid vehicles.

iii) Cost of Advanced Powertrain Components

Components such as batteries, fuel cells, and electric motors remain expensive, driving up the overall cost of electric and hydrogen-powered vehicles. While costs are expected to decrease with advancements in manufacturing and economies of scale, the current price premium compared to traditional vehicles remains a significant barrier for widespread adoption.

1. Hydrogen Infrastructure: Hydrogen-powered vehicles, despite their potential for long-range applications and fast refuelling times, face the challenge of insufficient refuelling infrastructure. The development of a global hydrogen refuelling network is capital and resource-intensive, hindering widespread consumer acceptance and adoption.
2. Consumer Acceptance and Perception:

Many consumers are still hesitant to embrace new powertrain technologies due to concerns about reliability, range anxiety (for EVs), refuelling convenience (for hydrogen vehicles), and overall cost. Overcoming these psychological barriers requires clear communication, incentives, and widespread availability of advanced powertrain vehicles.

B. The Future of Advanced Powertrains

i) Advancements in Battery Technology:

Future developments in solid-state batteries and lithium-sulfur technologies are expected to offer greater energy densities, faster charging times, and lower costs. These advancements will further enhance the range and performance of EVs and hybrids, making them more competitive with traditional vehicles.

ii) Integration of Renewable Energy Sources:

The growth of renewable energy sources, such as solar and wind, will complement the adoption of electric and hydrogen-powered vehicles. As electricity generation becomes cleaner and more sustainable, the carbon footprint of electric vehicles will be further reduced, enhancing their environmental benefits.

iii) Hydrogen and Electric Powertrain Integration

In the future, we may see more hybrid solutions that combine hydrogen and electric powertrains, offering the benefits of both technologies. Hydrogen could be used as an auxiliary power source or to extend the range of electric vehicles, enabling optimal energy use in different driving conditions.

iv) Autonomous Vehicles and Advanced Powertrains

As autonomous driving technology advances, it will likely be paired with advanced powertrain technologies. Fully electric or hydrogen-powered autonomous vehicles will benefit from the efficiency, quiet operation, and smooth energy transitions provided by electric and hydrogen systems.

v) Sustainability and Circular Economy:

The future of advanced powertrains will be shaped by a greater emphasis on sustainability and circular economy principles. This includes improving the recyclability of battery materials, using sustainable materials in manufacturing, and creating closed-loop systems for electric vehicle components.

vi) Regenerative Braking Technology: Regenerative braking is a process where the kinetic energy of a vehicle during braking is captured and converted into electrical energy. Instead of being wasted as heat like in traditional brakes, this energy is fed back into the battery for reuse. This technology is common in hybrid and electric vehicles and improves overall efficiency and range.

IV. CONCLUSION

The future of advanced powertrains is undeniably promising, as rapid technological innovation and increasing regulatory pressure continue to reshape the landscape of the global automotive industry. The transition from traditional internal combustion engines to electrified and alternative powertrain systems is not merely a trend—it represents a fundamental shift toward more sustainable, energy-efficient, and environmentally conscious transportation solutions. Hybrid Electric Vehicles (HEVs), Battery Electric Vehicles (BEVs), and Fuel Cell Electric Vehicles (FCEVs) are emerging as viable alternatives that offer substantial improvements in fuel economy, lower greenhouse gas emissions, and enhanced

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Automated Diagnostic Imaging: Enhancing Medical Interpretations through Deep Learning

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ABSTRACT

Deep learning techniques have revolutionized medical imaging diagnostics. This paper presents a novel approach to automated diagnostic imaging using convolutional neural networks (CNNs). Our proposed model enhances medical interpretations by improving image quality, detecting abnormalities, and providing accurate diagnoses. This paper could aim to analyze how deep learning models are revolutionizing diagnostic imaging in healthcare. It would focus on automated interpretation systems, enhancing diagnostic accuracy, reducing human error, and improving patient outcomes. this paper presents detection and classification of multiple diseases, as well as medical imaging modalities, evaluation tools and techniques, and dataset descriptions. In addition, experiments employing the MRI dataset are carried out in order to provide a comparison of DL models and ML classifiers.

Index Terms — Medical Image Detection, Analysis , Deep Learning, Simulation Tool Details

I INTRODUCTION

Medical imaging plays a vital role in disease diagnosis. Recent advancements in Machine Learning (ML) and Deep Learning (DL) have improved disease detection and classification accuracy. This overview explores various ML and DL approaches for multi-disease detection, classification, and medical imaging modalities. This overview provides a comprehensive review of ML and DL approaches, medical imaging modalities, and evaluation techniques. Experimental analysis using MRI dataset offers insights into comparative performance of ML classifiers and DL models.

Overview of Diagnostic Imaging

Diagnostic imaging plays a critical role in modern medicine, providing non-invasive methods to visualize the internal structures of the body. Techniques like Computed Tomography (CT), Magnetic Resonance Imaging (MRI), X-rays, and Ultrasound are widely used to detect, diagnose, and monitor diseases. CT scans offer detailed cross-sectional images of bones, blood vessels, and soft tissues, while MRI provides high-resolution images of organs, particularly the brain and spine. X-rays are commonly used for bone fractures and chest conditions, while Ultrasound is vital in prenatal care and soft tissue examinations. These imaging modalities have revolutionized healthcare, allowing doctors to make informed decisions without the need for exploratory surgery.

Challenges in Traditional Diagnostic Imaging

Despite its benefits, traditional diagnostic imaging is not without its challenges. Human interpretation is often subject to variability, leading to diagnostic errors. Different radiologists may arrive at varying conclusions based on the same image, influenced by factors such as experience, fatigue, and environmental conditions. Additionally, interpretation delays due to high workloads or the need for second opinions can affect patient outcomes, particularly in time-sensitive cases like trauma or stroke. These limitations highlight the need for more accurate and efficient systems to support radiologists and healthcare professionals.

Introduction to Deep Learning

Deep learning, a subset of artificial intelligence, has emerged as a powerful tool to address these challenges in diagnostic imaging. It involves the use of neural networks, particularly convolutional neural networks (CNNs), which are highly effective in analyzing visual data like medical images. CNNs automatically learn to recognize patterns and features in imaging data without the need for manual intervention. By training on large datasets of annotated medical images, these models can achieve a level of accuracy comparable to human radiologists, and in some cases, outperform them. Deep learning models are being used to detect anomalies such as tumors, fractures, and organ abnormalities, making medical interpretation faster, more consistent, and less prone to human error.
This convergence of deep learning and medical imaging holds immense potential in transforming the field of diagnostics by providing automated, reliable, and scalable solutions for healthcare systems globally.

This research work most significant contributions include:

(i) Disease classification after reviewing primary studies; (ii) Recognition of various image modalities provided by existing articles; (iii) Dataset description to make people aware of sources; (v) Experimental results using an MRI dataset to compare various ML and DL methods; (vi) Selection of suitable features and classifiers to get better accuracy; (vii) Perspectives on classification and a review of methods for inferring future research.

It is impossible to overstate the significance of employing cutting-edge DL techniques in the field of medical image analysis. DL is particularly noteworthy for medical image analysis in the healthcare industry because it has achieved impressive results in a variety of areas. Real-time analysis of vast and intricate datasets is made possible by combining DL with medical image analysis, which results in insights that significantly improve healthcare outcomes and industry operational efficiency. The most recent deep learning (DL) strategies developed to address challenges in medical healthcare are examined in depth in this comprehensive literature review, with a particular focus on the application of deep learning algorithms to medical image analysis. We have evaluated each of the investigated papers based on a few crucial parameters, dividing them into five distinct techniques categories.

I DEP LEARNING BASED MEDICAL IMAGE ANALYSIS: AUTOMATED DIGNOSIS AND PROGNOSIS

A subfield of machine learning known as "deep learning" makes use of multiple-layer artificial neural networks to identify intricate patterns in large datasets (1, 2). (3). Deep learning's ability to learn features automatically from raw data eliminates the need for manual feature engineering, which is one of its primary benefits. Because of this, it is particularly effective in domains with large, complex datasets, where conventional machine learning approaches may have difficulty capturing the underlying patterns Image and speech recognition, natural language comprehension, and the development of autonomous driving capabilities are just a few of the many areas where deep learning has facilitated significant advancements. For instance, deep learning has made it possible to create extremely precise computer vision systems that can identify objects in videos and images with an unmatched level of precision. In a similar vein, deep learning has significantly improved natural language processing, resulting in the creation of models that are able to comprehend and produce language that is comparable to human expression (7).

The processing, interpretation, and analysis of medical images are all part of the field of study known as medical image analysis. In recent years, the use of deep learning algorithms to improve the diagnosis, treatment, and monitoring of a wide range of medical conditions has led to a significant shift in the field of medical image analysis (9). As a subfield of machine learning, deep learning encompasses the training of algorithms to extract knowledge from large amounts of data. Deep learning algorithms can automatically identify and classify anomalies in various medical images, such as X-rays, MRI scans, CT scans, and ultrasound images, when applied to medical image analysis (10). Large datasets of annotated medical images can be used to train these algorithms, with labels attached to each image describing the corresponding medical condition or abnormality (11). The algorithm can analyze new medical images and provide healthcare Studies demonstrating high levels of accuracy in detecting and diagnosing a wide range of medical conditions indicate that the application of deep learning algorithms in medical image analysis has produced promising results (12).

The development and implementation of algorithms and techniques for analyzing and deciphering medical images are all part of the field of study known as "medical image processing" (14). Various aspects of medical image processing include segmentation, registration, feature extraction, classification, and visualization. The primary goal of medical image processing is to extract useful data from medical images, making it easier to diagnose, plan treatment, and implement therapeutic interventions. Each modality has its own advantages and disadvantages, and in order to extract useful information from the images produced by various modalities, particular processing methods may be required (16). By making it possible to view and analyze the internal structures and functions of the body in a non-invasive manner, medical image processing techniques have revolutionized the medical field. Early disease detection and diagnosis, precise treatment planning, and treatment response monitoring have all been made possible by it.

The use of medical image processing has led to significant improvements in patient outcomes, a reduction in the price of treatment, and an increase in the quality of patient care. In the context of DL algorithms for medical image analysis, visual representations of CNNs depict a layered architecture in which the initial layers capture basic features like edges and textures and the subsequent layers gradually discern more complex and abstract characteristics. This allows the network to autonomously extract relevant information from medical images for tasks like detection, segmentation, and classification.

The role of image analysis in medical healthcare

The advanced and automated analysis of medical images made possible by the use of deep learning algorithms for image analysis has revolutionized medical healthcare (20). Convolutional neural networks (CNNs) and other deep learning techniques have demonstrated remarkable performance in image segmentation, feature extraction, and classification tasks. Deep learning models can learn intricate patterns and relationships in medical images by using a lot of annotated data. This makes it easier to find diseases and abnormalities, pinpoint them, and make a diagnosis. Improved patient outcomes, personalized treatment planning, and efficient healthcare workflows are all made possible by the faster and more precise interpretation of medical images made possible by deep learning-based image analysis (22). By analyzing massive image datasets, these algorithms could also improve medical research, assist radiologists in making decisions, and aid in early disease detection. In general, deep learning-based image analysis is reshaping medical healthcare by providing powerful image interpretation tools, enhancing healthcare professionals' capabilities, and improving patient care (23).

Medical image analysis application

Medical image analysis with deep learning algorithms has found numerous applications in the healthcare industry. Convolutional Neural Networks (CNNs) and other deep learning methods have been widely used for image segmentation, object detection, disease classification, and image reconstruction (24). These algorithms can help identify and diagnose a variety of conditions, including tumors, lesions, anatomical abnormalities, and pathological changes, in medical image analysis. They can also be helpful in determining the prognosis, treatment response, and progression of the disease. In order to facilitate efficient and accurate interpretation, deep learning models are able to automatically extract meaningful features from medical images (25). Clinical decision-making can be improved, patient outcomes can be improved, and resource allocation in healthcare settings can be optimized through the application of this technology. In addition, deep learning algorithms can be used for multimodal fusion, data augmentation, image registration, and comprehensive and integrated analysis of medical images from a variety of modalities. Medical image analysis is making significant progress thanks to ongoing advancements in deep learning algorithms. This is opening up new opportunities for precision medicine, personalized treatment planning, and advanced healthcare solutions (26).

III Related Work

This is something that Singh et al. 24) emphasized the significance of machine learning (ML) and artificial intelligence (AI) in advancing the design of biomedical materials and predicting their toxicity. The authors emphasized the need for safe and effective materials for medical applications and how computational techniques can help with this. Random forests, decision trees, and support vector machines, among other AI and ML algorithms that can be used to predict toxicity, were examined in the paper. The authors provided a case study in which they predicted carbon nanotube toxicity using a random forest algorithm. In addition, they emphasized the necessity of AI/ML models' interpretability and transparency, as well as the importance of data quality and quantity for accurate predictions. The integration of multi-omics data, network analysis, and deep learning methods were all discussed as potential future research directions in this field at the conclusion of the paper. This study demonstrated how AI/ML could reduce the need for animal testing and advance biomedical material design.

moreover, Jena et al. 25) looked into how the parameters a smart healthcare system used to classify diabetic retinopathy (DR) affected how well deep learning models performed. The researchers created a convolutional neural network (CNN) architecture with two branches to classify diabetic retinopathy (DR) using images of the retinal fundus. The proposed model includes both a classification branch and a feature extraction branch. In the feature extraction branch, a pre-trained model is used to extract relevant characteristics from the input picture. These features are then used by the classification branch to predict the severity of DR. In order to assess the model's performance, the authors experimented with the optimizer, batch size, learning rate, and number of epochs. When the best parameter configuration was used, the results showed that the suggested model had an accuracy of 98.12 percent. A secure IoT-based blockchain-based smart healthcare system for processing and storing medical data was also suggested by the authors. Patients' outcomes could be improved by using the proposed system for early DR diagnosis and treatment.

Additionally, Thilagam et al. 26) presented a deep learning-based access control system and a secure Internet of Things (IoT) healthcare architecture. The sensitive medical data stored in IoT devices will only be accessible by authorized personnel thanks to the proposed system. A robust access control system that can identify and authenticate users with high accuracy was developed by the authors using deep learning algorithms. Additionally, the system contained an encryption layer to guarantee the safety of all data exchanged between devices. Through a prototype implementation, the authors evaluated the proposed architecture and discovered that the system can securely access real-time medical data. In addition, the authors compared their approach to other solutions and demonstrated that it performs better in terms of accuracy, safety, and scalability. The paper emphasized the possibility of incorporating deep learning algorithms into healthcare systems to improve privacy and security while also making it easier to access medical data in real time.

In addition, Ismail et al. 27) came up with a CNN-based model for looking at common health factors in an IoMT (Internet of Medical Things) setting. Using CNN-based algorithms, the model extracted features from a variety of health data sources, including body temperature, pulse rate, and blood pressure. These features are then used to predict the likelihood of health issues. There are five types of health data that the proposed model can classify: normal, with pre-diabetes, diabetes, hypertension, and hypertension. In order to train and evaluate the model, the authors made use of a real-world dataset that included health data from fifty individuals. According to the findings, the proposed model outperformed existing machine learning models in terms of predictive accuracy and computational complexity. It also exhibited a remarkable level of accuracy. The authors expressed their optimism that the proposed model could advance health monitoring systems that provide personalized interventions and real-time monitoring, thereby reducing health risks and improving patient outcomes.

More, S, Singla, J, Verma, 28) proposed a CNN-based security-assured model for reconstructing medical images on the Internet of Healthcare Things (IoHT) with the intention of protecting medical data's privacy and security. There are two main components to the proposed framework: a security-enhanced encryption model and a deep learning-based image reconstruction model. A convolutional neural network (CNN) is used by the image reconstruction model to precisely reconstruct original medical images from compressed versions. The encryption model uses a hybrid encryption scheme that combines symmetric and asymmetric methods to protect the transmitted images. The model's remarkable reconstruction accuracy and effective security performance were demonstrated through evaluation with a widely used medical imaging dataset. This study emphasizes the critical need to ensure the security and privacy of medical data while also highlighting the potential of using deep learning models in healthcare, particularly in medical image processing.

IV. Simulation Tools details

It was discovered that image modalities like MRI, CT-Scan, X-Rays, and soon have been utilized in various techniques. Programming languages like R, MATLAB, and Python were also used to automate the process of segmenting and classifying images in order to get accurate results.

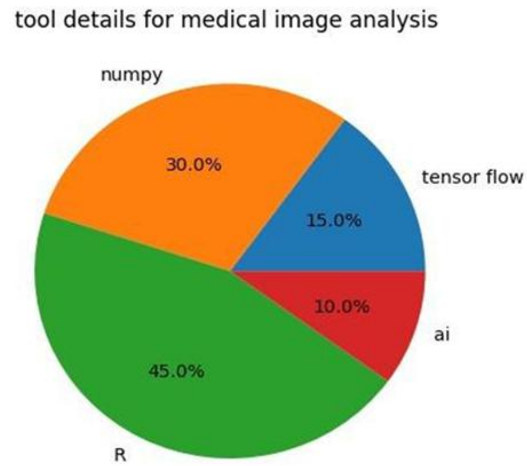


fig 1.0 simulation tool details for diagnosis and prognosis of medical images automated rectifying

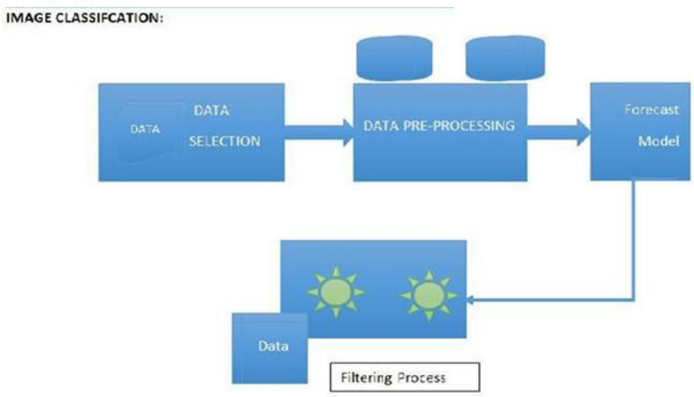
The method that was used to conduct this review in a systematic manner is discussed in detail. It details the electronic databases used to search for information, retrieve it, and talk about the research questions formulated to carry out the review successfully. This literature review was conducted in accordance with the guidelines for a systematic review developed by [29, 30]. Advances in methods for analyzing medical images make it possible for machines to achieve the accuracy achieved by DL models. In 1958, the labelled chest X-rays were used to diagnose heart disease, and the cardiologist reviewed and relabelled all of the data, discarding anything other than heart failure and normal images.

As depicted in the figures, ML and DL methods were utilized to process the medical images for improved prediction and accuracy. 1 and 2, specifically. Medical images from a variety of modalities are used as input, and algorithms are then applied to these images. In addition, the input image was segmented based on a variety of factors, and feature extraction techniques were used to extract the essential and maximum features from these segments. After the necessary features are extracted, they are further refined to produce the actual features used to identify diseases [31]. In addition, medical images were denoised using ML techniques in [32] for improved prediction and accuracy. Classifying the images according to the disease using classifiers like SVM, Decision Tree (DT), and so on follows the selection of features and the removal of noise from the data. was achieved.

Computers learn from data and use algorithms to complete a task without being explicitly programmed through the process known as machine learning (ML). It uses a new dataset and pattern recognition to make predictions. In contrast, DL is modeled after the human brain and includes a complex structure of algorithms that enable machines to process documents, images, and text. It makes use of algorithms with layered structures like the Convolutional Neural Network (CNN), Artificial Neural Network (ANN), and so on, to apply logic to the data analysis. In comparison, DL models are less effective at processing large amounts of data than ML models.

ML/DL techniques for medical image analysis

Convolution neural networks (CNNs) play a significant role in the utilization of deep learning strategies for the processing of medical images. Due to their ability to automatically extract relevant characteristics from intricate medical images, they perform well in tasks like object localization, segmentation, and classification. By capturing intricate patterns and structures, CNNs are able to accurately identify anomalies, diagnose tumors, and segment organs in medical images. Using CNNs' hierarchical structure, important characteristics can be learned at multiple levels, enhancing analysis and diagnosis. The use of CNNs in medical image analysis has significantly enhanced the accuracy, efficiency, and automation of diagnostic procedures, resulting in favorable outcomes for patient care and treatment.



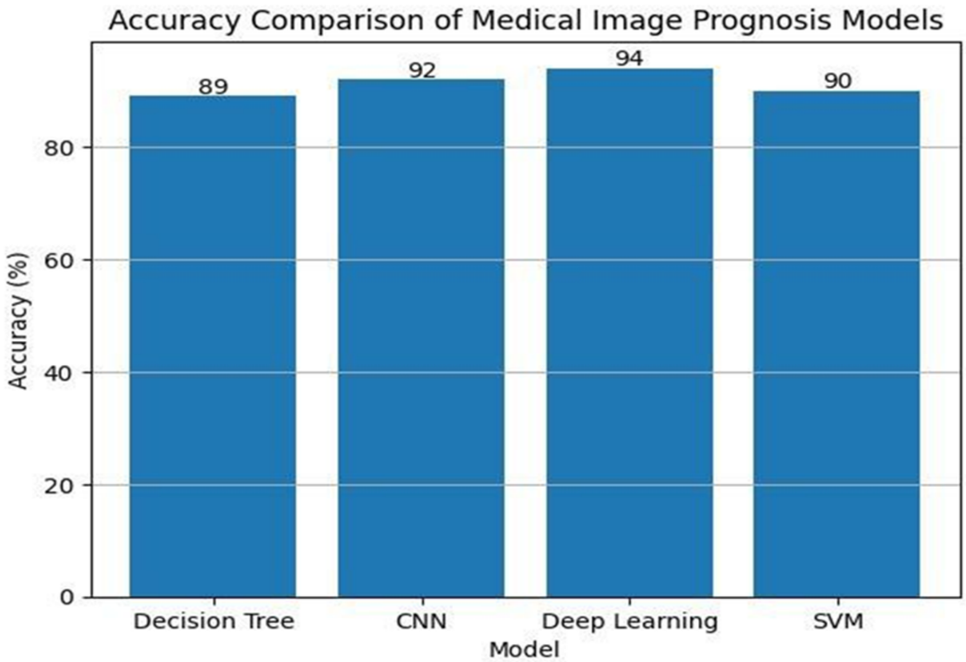


Fig 1.1, 1.2 graph show various ML algorithms based medical images detection accuracy percentile ration on the basis of previous studies

V. CONCLUSION

Classification, imaging modalities, tools, techniques, datasets, and obstacles in the medical domain are all discussed in this study, as are various ML and DL approaches to disease diagnosis. The most frequently used diagnostic modalities are MRI and X-ray scans. Additionally, MATLAB and SVM dominated the study's tools and techniques, respectively. Researchers use the MRI dataset a lot, it was found. Additionally, a comparison of ML classifiers and DL models was conducted through a series of experiments using an MRI dataset. The results showed that CNN and RF performed better than other algorithms. It also comes to the conclusion that a variety of traditional ML and DL methods are frequently used to deal with data uncertainty. DL approaches have recently gained a lot of popularity among researchers due to their superior performance. This review will help the healthcare community, physicians, clinicians, and medical practitioners select a suitable ML and DL method for rapid and accurate disease diagnosis.

VI. FUTURE SCOPE

The investigation aims to provide valuable guidance for future research on DL application in medical and healthcare image analysis. Future aspect of forecasting medical images analysis and found prediction level of early find disease.

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