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Synthesis of Metal Oxide Nanoparticles using Indian Medicinal Plants for Photocatalytic Applications - A Review

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ABSTRACT

The green route based on plant extracts has been regarded a valuable alternative to traditional methods for nanoparticle synthesis due to its low cost, biocompatibility, scalability, and absence of the need for additional stabilising agents during nanoparticle creation. In considerable concentrations, plant extracts contain several phytochemicals such as phenols, alkaloids, terpenoids, and tannins, as well as numerous vitamins. During the creation of metal nanoparticles from their respective precursors, these phytochemicals operate as reducing, capping, and stabilising agents. Even if photocatalytic processes are an useful technique for treating harmful organic pollutants, the bulk of present photocatalysts are unable to exploit sunlight enough to accomplish the destruction of these pollutants. According to a number of researchers, metal oxide nanoparticles have substantial photocatalytic activity when exposed to visible light. Among the several chemical and physical processes used to synthesis nanostructured metal oxide, the green synthetic pathway is the most cost-effective and eco-friendly.

Keywords: Fluent, Intake, Manifold, Runners

I. INTRODUCTION

Metal and metal oxide nanoparticles have unique properties, such as catalytic activity, thermal conductivity, optical, mechanical, and electronic properties, as well as biological activity (anti-bacterial, anti-fungal, anti-viral), due to their higher surface area to volume ratio, specific composition, shape, and size [1–3]. These distinctive features make them extremely helpful in a variety of fields, including water pollution remediation, electrical, medical, self-cleaning, electrochemical sensing, and agricultural technology [4–7]. Several methods, including chemical wet processing, thermal reduction, micro-emulsion techniques, biosynthetic procedures employing microorganisms (bacteria and fungi), and plant extracts, have been described in the scientific literature [8–11]. Compared to chemical wet processing or physical routes of synthesis, plant-mediated (using extracts of natural plants) synthesis of metal nanoparticles is superior in terms of biocompatibility, non-toxic reagents, low energy requirement, rapid synthesis, ease of processing, scalability, and long-term stability of synthesised nanoparticles [12]. By adapting a green synthesis method based on plant extracts, the requirement for surfactants and stabilising chemicals can be eliminated during nanoparticle creation. The key phytochemical constituents (terpenoids, alkaloids, steroids, flavonoids, sugars, and their derivative molecules) found in plant extracts with amino, hydroxyl, carboxylic, allyl, alkoxy, and sulfhydryl groups are not only useful as a reducing agent in the synthesis of metallic nanoparticles, but also as a stabilising agent to maintain the long-term reactivity of nanoparticles. Green nanotechnology is the ideal method to reduce the negative impacts of nanomaterial manufacturing and application, hence reducing the nanotechnology's riskiness [13]. Nanotechnology and materials science have made a significant advancement with the creation of nanomaterials. These products should be introduced into the real world by leaving the laboratory. There are thousands of such goods on the market, the most majority of which are incorporated into personal care products, cosmetics, and clothes. Almost every industry and manufacturing area, including medicine and drug distribution, is anticipated to benefit from the development of modern items that customers require. It is evident that the nanomaterials market and nano-assisted devices continue to expand [14]. The commercialization of successful disruptive technologies is essential for multiple human applications and global development, but important attention must be paid to the potential, health evaluation, and environmental repercussions of these substances [15]. It is an undeniable fact that the health risks associated with nanoparticle exposure are slowly understood and must be addressed immediately [16], and that their production and use are practically uncontrolled [17], particularly in the growth of the cosmos. This is primarily discouraging when new nano-based entities are being generated and incorporated into consumer products at an alarming rate; therefore, oversight mechanisms are urgently required, as the final existence of the majority of nanotechnology innovations resulting from research groups that considered simple start-up work must be based on instructions and recommendations from regulatory bodies and should not be adversely affected by the increased cost. Health and safety laws will have to carefully negotiate regulatory testing cost burden, which will play a crucial role in assigning nanomaterial-related dangers priority [19].

Green synthesis of metal nanoparticles using extracts of natural plants

Typically, ethanol or distilled water are employed as solvents in the production of cobalt nanoparticles from plant extracts derived from various plant components such as flowers, bark, root, leaves, fruit peels, and fruit pulp. In general, the green routes for metal nanoparticles synthesis utilising natural plant extracts are segmented according to the sequential processing steps depicted in Figure 1. The initial step in the manufacturing of extracts is the washing of selected plant parts (flowers, bark, root, leaves, fruit peels, fruit pulp, etc.), followed by drying and powderization by cutting or grinding. Certain plant sections were typically washed with tap water followed by distilled water to remove debris, epiphytes, and dust from their surfaces. Next, the powdered plant parts are boiled at a given temperature with a specific volume of necessary solvents (deionized water, methanol, ethanol etc.). After a certain period of boiling, filtration is required to isolate phytochemicals (phenolic acids, alkaloids, steroids, flavonoids, sugars and their derivative molecules with amino, hydroxyl, carboxyl, allyl, alkoxy and sulfahydril groups) in desired solvents that exist in specific plant parts [20].

The bio variations of plants provide an abundance of biochemical properties and introduce a specific source for the synthesis of nanoparticles [21]. Numerous metabolites serve as reducing agents in the synthesis of nanoparticles [22] and can be readily extracted from the leaf of the plant. At room temperature, a solution containing metals such as nickel, cobalt, zinc, and copper is combined with the extract of the plant leaf [23]. Several variables, including pH, temperature, contact time, metal salt content, and phytochemical profile of the plant leaf particles, influence the quality, stability, quantity, and yield rate of nanoparticles. Due to the presence of water-soluble phytochemicals, metal ion reduction in plants occurs more rapidly than in fungi and bacteria, which require a lengthy incubation period [24]. Numerous phytochemicals included in plant leaf extracts may be extracted easily [25], hence plant leaf extracts are regarded as an excellent tool for the creation of metal nanoparticles. The ability of plant leaf extracts to act as stabilising and reducing agents promotes the creation of nanoparticles [26].

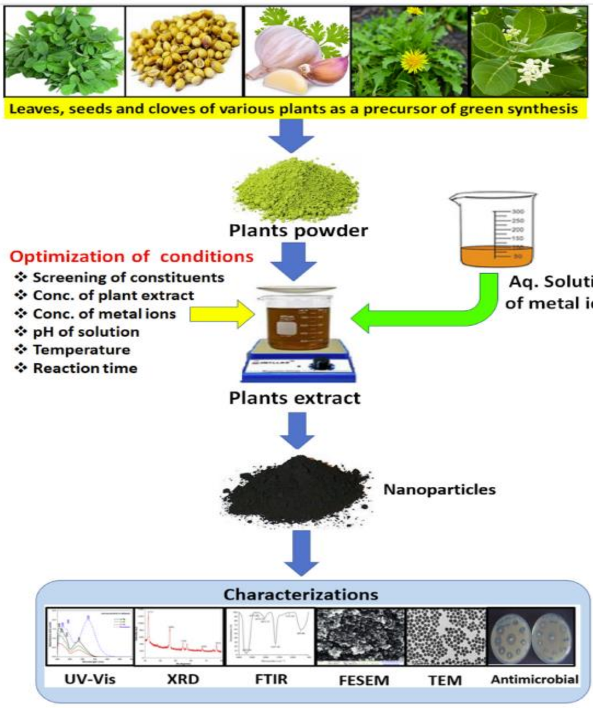

Figure 1. Schematic representation of metal nanoparticle synthesis using natural plant extracts approach [Ref. 29].

Various types of leaf extracts contain different quantities of biomedical reducing agents, hence the composition of leaf extracts has a significant impact on nanoparticle creation [27-28]. Terpenoids, flavones, ketones, amides, aldehydes, and carboxylic acids are crucial phytochemicals in the creation of nanoparticles.

Advantages of using plant extracts in nanoparticle synthesis

Biosynthesis is an environmentally friendly synthetic process that can be categorised as a bottom-up process in which metal atoms join to form clusters and eventually nanoparticles. The biosynthetic technique is similar to the chemical reduction process, however plant extracts are used to produce nanoparticles instead of expensive and toxic chemicals. By monitoring the hazardous response, a comparative investigation distinguished between the chemical reduction of AgNPs utilising green synthesis using plant extracts and conventional wet chemistry. The cytotoxicity and phytotoxicity of the AgNPs produced by green synthesis were much lower than those produced by wet chemistry, confirming that green AgNPs are safer and can be employed extensively in biomedical areas, particularly cancer fields. Consequently, as a result of these factors and the growing acknowledgement of the significance of fundamental green chemistry approaches, biological synthesis has been regarded as a promising eco-friendly alternative that looks to provide the most advantageous methodology and results. A diverse collection of organisms found in nature, including plants, algae, fungi, yeast, bacteria, and microorganisms [30,31]. Since ancient times, nature has offered numerous unique resources that have benefited human life. Primarily produced from plants and microorganisms are the naturally available reagents that can be used in biosynthesis and green chemistry-based processes for material bio-fabrication. It has been claimed that several biological entities, such as plants, bacteria, fungi, seaweed, and microalgae, have successfully synthesised various metal and metal oxide nanoparticles. Among these entities, plant extracts have garnered a great deal of interest due to their simplicity, low cost, and rapid reaction time, as well as their ability to convert metal ions into metal nanoparticles and their potential to produce nanoparticles in vast quantities. Moreover, plant extracts allow for the manipulation of nanoparticle formation to generate well-defined sizes and morphologies in a single-step, high-yield synthesis [32-38].

Numerous investigations on the synthesis of biological entities have revealed that size and morphology can be more precisely determined than with some physical and chemical procedures [39]. The well-defined morphology structure of AuNPs by manipulating the synthetic parameters, i.e., effect of boiling time of plant extract (Illicium verum), pH effect, extract ageing effect, and temperature; comparison studies between AuNP synthesis using plant extract and common wet-chemical methods that use sodium borohydride and sodium citrate, respectively. Using plant extracts, they quickly generated monodisperse AuNPs of diverse triangular, hexagonal, and pentagonal forms with sizes ranging from 20 to 50 nm, whilst the platelets ranged in size from 30 to 50 nm [40].

Surprisingly, AuNPs manufactured utilising plants are less harmful than AuNPs synthesised using sodium borohydride and sodium citrate. In addition, Jamuna et al. [41] generated biocompatible and nontoxic anatase phase titanium dioxide spherical nanocrystals from Desmodium gangeticum root aqueous extract. Numerous researchers have discovered that the metal nanoparticles derived from plant extracts are not only harmless and biocompatible with normal human cells, but also permit targeted drug administration via nanoparticle localization and can exhibit antibacterial, antiviral, and antitumor characteristics [42]. Muniyappan and Nagarajan [43] and Ahmad et al [44] produced AuNPs from Curcuma pseudomontana essential oil and Mentha piperita leaf extract, respectively, which demonstrated drug delivery anticancer activity against cancer cell lines in addition to antibacterial, anti-inflammatory, and antioxidant properties. Consequently, the plant extract-mediated synthesis methodology meets all green synthesis criteria [Figure 2].

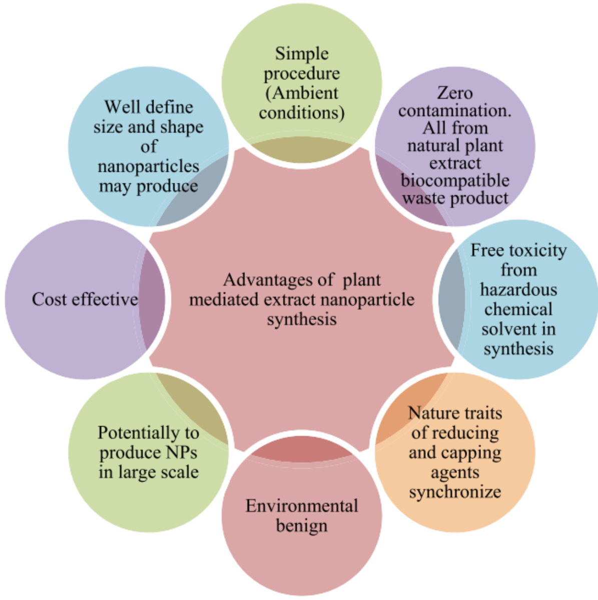

Figure 2. Advantages of plant extract-mediated nanoparticle synthesis (Ref. [45]).

Synthesis of metal oxide nanoparticles using medicinal plants

Due to their superior chemical, physical, and electrical qualities, metal oxides have witnessed accelerated growth in many industries and are widely employed in remediation of the environment, medical technology, energy technology, water treatment, and personal care goods. Consequently, the synthesis of a number of additional metal oxides from plant extracts has also been investigated. Using the plant extract of Aspalathus linearis, Ismail et al., [46] reported the synthesis of high-purity, quasi-monodisperse, spherical ruthenium (IV) oxide nanoparticles with an average diameter of 2.15 nm.

The optical band gap of the produced RuO2 NPs is 2.1 eV, and their surface area is 12.5 times greater than that of commercial particles. RuO2 nanoparticles also demonstrate an efficient photocatalytic watersplitting reaction in the solar spectrum. Yan D. et al. [47] described a green method for the manufacture of spherical Mn_3O_4 nanoparticles 20–50 nm in diameter using banana peel extracts. These nanoparticles displayed pseudocapacitive behaviour and satisfactory electrochemical performance. Kumari et al. [48] investigated various amounts of ripe pomegranate seed extract to produce quantum-confined SnO_2 NPs at room temperature with a tuneable band gap. With increasing annealing temperature, the SnO_2 NPs crystallised more and the average crystallite size grew. In addition, the SnO_2 NPs demonstrated improved thermal conductivity, greater radical scavenging activity during an in vitro antioxidant assay, and enhanced antibacterial activity.

In the case of lead (Pb), Elango et al. [49] were able to generate 47 nm spherical particles with robust antibacterial activity and excellent photocatalytic degradation of malachite green dye using a methanolic extract of agricultural waste from Cocos nucifera. Recently, spherical and ellipsoidal magnesium nanoparticles (Mg NPs) were synthesised from the flower extract of Hydrangea paniculata; these nanoparticles shown antibacterial and antioxidant activity against Escherichia coli and Staphylococcus aureus. Suranjit et al. [50] generated spherical, polydisperse, crystalline Se NPs with diameters ranging from 60 to 80 nm from lemon leaf extract and employed them as a potential chemotherapeutic agent in cancer therapy to prevent UV-induced DNA damage. In addition, Se NPs' fluorescent characteristic makes them valuable as a diagnostic agent.

Role of Nanotechnology in Photocatalysis

General Mechanism for Photocatalytic Reaction

A photo catalyst is utilised in photo-catalysis. The reaction rate is mostly determined by the crystalline structure of the catalyst and the energy of incoming visible or ultraviolet photons. Depending on their electronic structure, catalyst materials function as a light-sensitive sensitizer for light-stimulated redox processes. The filled valence and empty conduction bands characterise the electronic structure. If the band gap of the catalyst is equal to or less than the energy of the incident light, electrons in the valence band will absorb the photon and move to the conduction band. Holes are left in valence band. Donor molecules are oxidised by these holes, and when H_2O reacts with these holes, hydroxyl (a powerful oxidant) is generated. The conduction band electron is absorbed by water to produce the reducing agent superoxide ion. Thus, we can conclude that this free electron is responsible for redox processes. These pairs of free electrons and holes can transform any material that comes into touch with the catalyst into the desired products [51].

Oxidation Mechanism and Reduction Mechanism

When light is irradiated on a catalyst, an electron-hole pair is produced due to the promotion of valance electrons to the conduction band. The catalyst's resulting hole absorbs the water molecule and oxidises it into the highly reactive hydroxyl radical. If any organic contaminant is present, it will react with these hydroxyls and disintegrate. If the entire process occurs in the presence of oxygen, then intermediate radicals of organic molecules undergo chain reactions with oxygen molecules. In the case of organic pollutants, the end result is CO_2 and H_2O.

The pairing reaction constitutes the reduction of atmospheric oxygen. Oxygen is easily reducible, therefore its reduction can serve as an alternative to hydrogen production. Conduction band electrons react with oxygen to generate superoxide ion. The anion can also bind to the intermediate in an oxidation reaction that generates peroxides and then transform into water [52]. Compared to water, organic matter is more conducive to the reduction process. As illustrated in Figure 3, a large concentration of organic matter increases photocatalytic activity by raising the probability of the number of holes, hence decreasing the rate of carrier recombination.

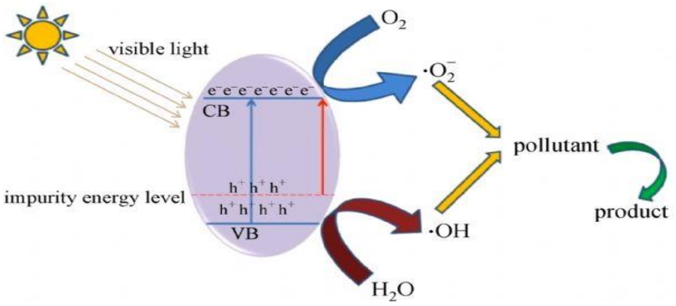

Figure 3. Scheme illustrating the three fundamental stages of the photocatalytic process [53]

Photocatalytic Experiment.

Researchers in the past have investigated the photocatalytic activity of Ag2O NPs utilising various organic dyes and contaminants. Decolorization of aqueous organic dyes and contaminants has been used to assess the photocatalytic activity of Ag2O NPs. The decolorization of aqueous solutions of organic dyes and contaminants by the photocatalytic activity of green synthetic samples was carried out at room temperature. The powdered Ag2O was disseminated in a solution of organic colours or contaminants made by dissolving the organic powders in deionized water. The test tube was put on the standing support in the darkroom of the photo reactor system at room temperature. As a light source, visible light was utilised. Before irradiation, the suspensions were magnetically agitated in the dark for a particular amount of time (often more than 40 minutes) to ensure the equilibrium of dye adsorption and desorption on the sample surfaces. The average light intensity impacting the reaction solution's surface should be sufficiently bright. After irradiation, solutions containing the sample powders and dyes were sampled every several seconds from the same tube. Then, the sample powders were separated by centrifugation, and the cleared dye solutions were analysed with a UV-Vis spectrophotometer to determine the concentration of the organic dyes by monitoring the height of the absorbance peak maximum in the solution's ultravioletvisible spectra [54]. The percentage of organic pollutant degradation can be calculated by

$$\text{degradation } (\%) = \frac{(A-B)}{A} \times 100$$

where A is the total of pollutants obtained without Ag2O NPs and B is the mount of pollutants with Ag2O NPs. Consequently, D (%) is the percentage of degradation, which indicates the photocatalytic efficiency [55].

Photocatalytic Activity and application of Ag_2O NPs

For healthy environment, it is highly necessary to preserve the ecological balance, in which regulating the environmental harmful pollutants is of considerable importance. Organizing a setup for photocatalytic activity for removal and detection of health-hazardous compounds from the environment as well as water remediation utilising semiconductor metal oxide is therefore a credible contribution of researchers to a better environment. Different researches have found that Ag2O is an excellent photocatalytic semiconductor for the breakdown of various organic contaminants. 160 minutes was determined to be the relatively lengthy degrading period for Ag2O NPs. These results demonstrate that the synthesised Ag as Ag2O had a high photocatalytic efficiency, which degraded MO in 10 minutes when exposed to visible light [56]. Jiang et al. [57] have disclosed a novel application for the Ag2O semiconductor, which demonstrates rapid photocatalytic capability to decompose MO in 120 seconds and high stability under visible and near-infrared light. Saha et al. [58] examined the full photocatalytic breakdown of Methyl Blue (MB) after 10 minutes utilising Ag2O nanoparticles produced from G. arborea fruit extract.

Bi et al. [59] investigated the photocatalytic degradation of non-AZO dyes on Ag2O and its acceleration by the addition of an AZO dye under visible light. In this work, the addition of methyl orange considerably reduced the photodegradation times of rhodamine B and methylene blue from 50 to 18 minutes and from 20 to 8 minutes, respectively. According to the findings of this study, this acceleration can be attributed to the synergistic impact of Ag2O and AZO species. According to the findings of this study, Ag2O is an exceptional visible light-driven photocatalyst for wastewater treatment. Thus, this fascinating phenomena is applicable to the use of Ag2O as a photocatalyst for the treatment of actual wastewater and could increase the viability of photocatalytic technology for environmental protection. All of these results are generalizable because both chemically and environmentally generated Ag2O nanoparticles demonstrate outstanding catalytic activity for the decomposition of toxic organic molecules. All of these research show that Ag2O has good photocatalytic performance and great stability for degrading organic contaminants and colours. In order to analyse the photocatalytic performance of Ag2O, the reference compound for photodecomposition was chosen to be methylene orange. The removal rates of MO from aqueous solution under visible light irradiation in Ag2O nanostructures and other photocatalysts employed as a comparison, including N-TiO2, were studied to rule out the influence of adsorption when assessing photocatalytic activity [60].

Photocatalytic Activity and application of ZnO NPs

Considering a future commercial application of ZnO in photocatalysis, the following limitations must be resolved: lack of visible light absorption, high e - h+ pair recombination rate, susceptibility to photo-corrosion, and solubility in strongly acidic and basic environments. To increase the photocatalytic performance of bare ZnO in terms of electron–hole recombination inhibition, large surface area, elimination of photo-corrosion, and high stability/reusability, it appears that coupling ZnO with 2D graphene compounds is the best of the available options (e.g., metal doping, nonmetal doping, coupling with other semiconductors, among others.). Using graphene to build composites with ZnO could provide numerous advantages, including effective charge separation and migration, prolonged light absorption, and enhanced photostability [61]. Despite the disadvantages indicated, ZnO is widely used as a photocatalyst. Considering the number of articles published on ZnO, graphene, and their composites, it is clear that the main focus is on the degradation of harmful pollutants (Figure 4), followed by the creation of H2 and the decrease of CO2. By the amount of articles devoted to the study of ZnO–graphene, it is evident that this research field is still in its infancy, despite the potential advantages of applying graphene to overcome ZnO's shortcomings.

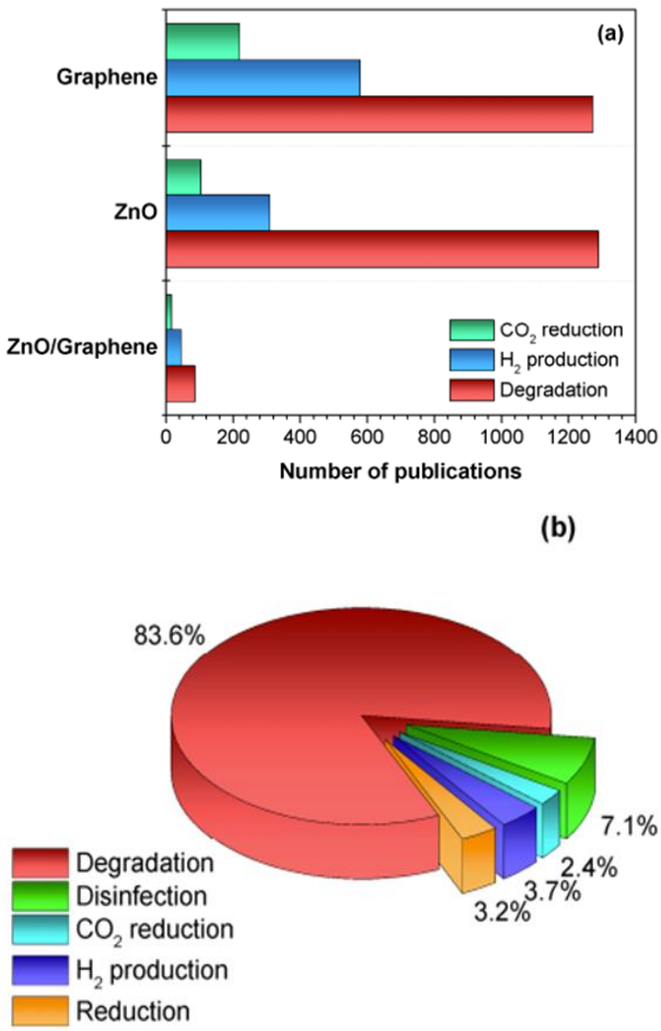

Figure 4. Number of publications about some photocatalytic applications of ZnO, graphene, and ZnO–graphene composites; (b) distribution of the publications devoted to several applications of the ZnO–Graphene composites in photocatalysis [62].

Water and air pollution are significant global health issues that require the removal or degradation of pollutants, including dyes, pesticides, pharmaceutical ingredients, organohalides, phenols, surfactants, heavy metal ions, agricultural waste, pathogens, volatile organic compounds, nitrogen oxides, carbon monoxide, sulphur monoxide, and ozone, among others, for which physical, physicochemical, biological, and chemical methods are used or investigated. Photocatalysis pertains to chemical procedures and is regarded as an advanced oxidation/reduction process, eliminating or degrading organic/inorganic chemicals that do not breakdown entirely when biological means are used [63]. It can produce a high concentration of reactive oxygen species (ROS) to completely oxidise the majority of organic molecules into carbon dioxide, water, and mineral acids. The shape of ZnO nanostructures plays an essential role in photocatalysis, which can significantly improve the photocatalytic efficacy compared to regular ZnO. In the case of ZnO rods, the exposure of a greater fraction of polar sides where hydroxyl ions are adsorbed and then converted into OH radicals explains its enhanced photocatalytic performance. However, as the majority of photocatalytic model reactions include the breakdown of dyes, it has not yet been determined if the 1D nanostructures of ZnO are optimal for the complete spectrum of reactions [64].

Photocatalytic Activity and application of CoO NPs

CoO-NPs are described as a multifunctional material having a normal spinal structure and a monoclinic structure. CoO-NPs are distinguished by their resistance to oxidation and corrosion, nontoxicity, affordability, and environmental friendliness. In recent years, CoO-NPs have been widely reported in a variety of applications, including heterogeneous catalysis (photocatalytic remediation of contaminated water), solar energy storage, magnetic semiconductors, supercapacitors, and electrochemical sensors [65]. The following section provides a summary of the utility of CoO-NPs in photocatalytic environmental applications for the treatment of contaminated water, electrochemical sensing, and antibacterial activities.

CoO NPs Photocatalytic degradation of dyes

Dyes are chemical compounds with specific functional groups (auxochromes, chromophores, conjugated system, etc.) and are widely employed as a colourant on diverse substrates such as fabric, paper, leather, etc. to create appealing products. Nonetheless, throughout the colouring process, a vast volume of dye-contaminated coloured wastewater is generated, which is a severe concern for all forms of life (people and animals) and the environment. Therefore, it is crucial to identify an effective approach for the cleanup of dye-contaminated water [66]. Surprisingly, the significant adsorptive and photocatalytic activity of CoO-NPs provided a novel approach to the remediation of dye-contaminated water. In recent years, a number of research on the breakdown or removal of dyes from contaminated water utilising CoO-NPs have been published. Adekunle et al. [67] studied the photocatalytic degradation of Erichrome Black-T and murexide dyes in aqueous solution when subjected to sunlight. Within 40 minutes of exposure to sunshine, only 10 mg of nanoparticles exhibited remarkable breakdown efficiency (39.4 percent). The authors discovered that dye molecules initially interact with nanoparticles, culminating in the adsorption process. As a result, photocatalytic breakdown of dye molecules required a longer period of exposure to sunshine. In another recent study, Samuel et al. [68] assessed the photocatalytic activity of CoO-NPs by observing the degradation of "Acid Blue-74 dye (cationic dye) in aqueous solution under the influence of UV light. In this study, CoO-NPs were produced utilising muscadine grape pulp extract (Vitis rotundifolia). The authors reported that produced nanoparticles were rhombus-shaped and exhibited a high photochemical degradation efficiency for acid blue-74 dye at a pH scale rise of 10 relative to the initial pH of the solution in the acidic range. The authors suggested that this phenomenon may be caused by the emergence of a distinct surface charge on the nanoparticles when the initial pH of the reaction solution increases. In addition, the authors noted that the formation of electron-hole pairs on the surface of nanoparticles and the transfer of charge between dye molecules and nanoparticle catalyst were the primary causes of the high photochemical degradation efficiency in the presence of UV light.

In addition to their photocatalytic efficacy, cobalt oxides can also be used to improve the photodegradation efficiency of other metallic nanoparticles by doping them in the proper concentration. Using an aqueous extract of Salvadora persica bark, Hanidian et al. [69] produced Cobalt-doped (1–10 wt%) CeO_2 nanoparticles. The wood of Salvadora persica is rich in trimethylamine, fluorine, fluoride, isothiocyanide compounds, sodium bicarbonate, tannins, and sulphur compounds. The authors also noticed that 7 percent Co doping with cerium nanoparticles not only effects the increase in surface area of the resulting nanomaterial, but also reduces the band gap. The addition of cobalt reduces the particle and crystallite sizes of the resulting nanoparticles, which is highly advantageous for extending the specific surface area and number of active sites. Thus, cobalt doping provides both benefits concurrently and accelerates photocatalytic performance. Therefore, based on the aforementioned results, it can be inferred that the cobalt nanoparticles with multifunctional surfaces are quite useful for the photocatalytic destruction of dyes in polluted water.

Conclusion and future prospects

In the past decade, the 'green' production of metal and metal oxide nanoparticles has been an extremely popular study topic. Numerous types of natural extracts (i.e., biocomponents such as plant, bacterium, fungi, yeast, and plant extract) have been utilised as effective resources for the synthesis and/or production of materials. It has been demonstrated that plant extracts are highly effective as stabilising and reducing agents for the synthesis of controlled compounds (i.e., controlled shapes, sizes, structures, and other specific features). This article was structured to cover the "state of the art" research on the "green" synthesis of metal/metal oxide nanoparticles and their applications in environmental remediation. Detailed synthesis mechanisms and an up-to-date literature review on the role of solvents in synthesis have been thoroughly evaluated based on the current literature in order to address the existing issues in "green" synthesis. In this article, a summary of recent research activities on the synthesis of metal oxide nanoparticles by phytochemicals derived from diverse plant extracts is provided. Due to the presence of important phytochemical ingredients in plant extract, there is no need for surfactants or stabilising agents during nanoparticle formation, as evidenced by the aforementioned research. Numerous efforts have been made to generate eco-friendly metal nanoparticles with increased photocatalytic activity, with applications in mind. However, additional research is required to overcome the current limits and meet the current expectations for multifunctional designed nanoparticles.

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