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A critical review on Efficiency of Metal oxide for Environmental and Biological Remediation

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Abstract

The unique physicochemical qualities of metal and metal oxide nanoparticles (MONPs), such as their huge surface area and morphological flexibility, high catalytic activity, and superior optical, physical, and biological capabilities, attracted a lot of attention. Their remarkable qualities have made them useful in a number of areas, such as medication delivery, antimicrobials, sensing, environmental cleanup, catalysis, and cancer therapy. Physical, chemical, and biological processes can all be used to create nanoparticles. Physical processes yield very pure nanoparticles, but they require sophisticated equipment and consume lots of energy. Through techniques including chemical reduction, sol-gel, hydrothermal, co-precipitation, and micro-emulsion, chemical synthesis provides a high degree of control over the shape, size, and content of nanoparticles. However, this approach produces hazardous outcomes and uses hazardous materials in several stages. The green approach, on the other hand, incorporates biological materials, plant extracts, bacteria, fungi, algae, and even agricultural waste in its operations, demonstrating affordability, sustainability, and environmental friendliness. The natural phytochemicals found in plant extracts, including flavonoids, phenols, alkaloids, terpenes, tannins, proteins, and carbohydrates, make them particularly promising. Compared to their products following traditional synthesis, green synthesis nanoparticles have been shown to be less poisonous, more stable, more compatible with living things, and to have a less environmental impact. Furthermore, because these nanomaterials can produce reactive oxygen species, cause apoptosis, and have cytotoxic effects on cancer cells, they have shown efficacy in photocatalytic degradation of organic compounds, their antibacterial qualities, targeted therapy, and cancer treatment.This article serves as a comprehensive review of the methods of synthesizing nanoparticles, discusses the principles of green synthesis, its biological sources, and presents various applications of metal oxide nanoparticles synthesized via green synthesis in medicine and environment, thus indicating their potential as sustainable materials for technological and clinical applications in the future.

Keyword : *Green synthesis, Metal oxide nanoparticles , Plant-mediated synthesis,Biogenic synthesis, Anticancer activity.*

1. Introduction

In nanotechnology, the production of nanoparticles (NPs) has gained popularity. NPs are attractive due to their versatile size and shape and exceptionally high surface area to volume ratio. The efficiency of nanoparticles is also related to their special properties, including their ability to conduct heat, electricity, and light as well as their catalytic efficiency. Metals and metal oxides, including gold, silver, nickel, copper, magnesium oxide, titanium dioxide (TiO_2), copper oxide, and zinc oxide (ZnO), are the NPs of major interest. These particles can be useful in chemistry, medicine, and materials science because they possess unique physical and chemical properties (Negrescu et al., 2022). Specifically, the metal oxide particles of interest include ZnO, TiO_2, CuO, Fe_3O_4, and MgO (Scrimin, 2021).Metal and metal oxide nanoparticles (NPs) are gaining popularity in the fields of biochemistry and medicine because of their application in areas such as catalysis, tissue engineering, and as antibacterial and anticancer agents. For instance, MgO nanoparticles have good stability, biocompatibility, and strong anti-pathogenic activity including antiviral, antimicrobial, and antifungal properties. Conventional techniques of production of these nanomaterials include chemical and physical methods, like sol-gel, hydrothermal, method precipitation as well as pyrolysis methods. However, although these methods are effective, they involve complicated manufacturing processes involving extreme conditions in the form of elevated temperatures, pressure, toxic solvents, and dangerous reducing or stabilizing agents implying the threat for both health and the environment. Metal nanoparticles (MNPs) and MONPs formed using these environmentally friendly methods are now frequently used in personal care products, cosmetics, medicines, drug-delivery, and textile industries, indicating their significant industrial application (Alsaiari et al., 2023). Green synthesis methods involve the use of microorganisms, plant extracts, proteins, and other biological agents that act as biocapping and bio-reducing agents, serving as "bio-nanofactories," which help in the preparation of nanoparticles at nanoscale level. These methods are eco-friendly, biocompatible, non-toxic, and cost-effective. Recent researches have shown that there have been major developments in the area of green synthesis using various biological materials such as bacteria, fungi, algae, and plants. Green synthesis of nanoparticles involves the use of biological entities such as bacteria, actinomycetes, fungi, yeast, algae and plant substances (El-Seedi et al., 2024). The goal of green synthesis is to preserve the environment and law by replacing harmful chemicals with environmentally friendly alternatives. Unlike traditional physical and chemical methods for nanoparticles synthesis, biosynthesis allows for better control over the size and shape of nanoparticles and incorporates the capping and stabilization influences that are produced by a variety of phytochemicals (Jadoun et al., 2021). As a consequence, green nanoparticles have useful applications in the capacity of antibacterial and photocatalytic substances as well as in adsorbents. In addition, green nanoparticles with magnetic properties are considered to be highly biocompatible and non-toxic for purposes of targeted drug delivery and contrast enhancement in magnetic resonance imaging as well as magnetic hyperthermia. In practice, many cases of successful fabrication of silver, gold, platinum and palladium nanoparticles using various biological extracts obtained from fungi, red algae, fruits and other natural objects are documented (El-Seedi et al., 2019). In traditional methods of synthesis of nanoparticles, various chemical reduction methods like sodium borohydride reduction, sonochemistry, laser ablation and sputtering are used. Although these techniques work well, they also entail the usage of harmful substances, dangerous residues, and complicated processes with high consumption of power. On the contrary, the method of green synthesis implies the use of organic materials (plant extract, algae, fungus, or microorganisms) as substances that reduce materials and stabilize the process (Lithi et al., 2025). The process of the creation of green nanoparticles is based on the precepts of the environmental science, which help the process to be safer, more economical, and ecologically friendly. The first aspect is the usage of non-toxic solvents, predominantly water, which is a natural solvent for the extraction of active components and is safe when compared to organic solvents (Radulescu et al., 2023). The second important point is the use of organic reducing and stabilizing agents from plants, algae, fungi, or microorganisms that contain many biomolecules, such as phenolics, flavonoids, terpenoids, polysaccharides, amino acids, alkaloids, and proteins that are able to reduce metal ions and stabilize the process. The green way of synthesis also provides the usage of the renewable source, more specifically, leaves, flowers, seeds, fruits peels, and algae as they are cheap and eco-friendly resources. The methodological approach is based on multiple general principles such as waste generation reduction or elimination, use of non-toxic or low-toxicity materials, use of renewable biological resources, minimization of energy use through easy processing conditions (for example, room-temperature or sunlight-assisted synthesis), and prevention of secondary product formation. As the demand for the sustainable production of nanomaterials rises, green synthesis is becoming one of the preferred methods, especially since traditional methods generally involve the use of toxic reagents and environmentally harmful processes. Green synthesis is well-matched with the fundamental principles of green chemistry which include the use of water as a safe solvent, use of biomolecules for reduction and capping, reduced energy requirements, and the use of renewable resources. The different biomolecules found in natural extracts such as phenolic compounds, flavonoids, terpenoids, amino acids, alkaloids, polysaccharides are important in reduction, chelation, and stabilization processes that occur during the synthesis of nanoparticles. The evolution of these eco-friendly methods has been traced back to the early 2000s when Anastas and Warner introduced the Twelve Principles of Green Chemistry in their landmark book Green Chemistry.

- Waste generation must be stopped by taking preventative measures; • Atom Economy The final product should incorporate as many of the synthesis elements as possible;
- Less Hazardous Chemical Synthesis: Synthesis techniques that call for ingredients with little to no toxicity to people or the environment should be prioritized;
- Creating Safer Chemicals: Materials should be created to perform with little to no toxicity;
- Safer Solvents When feasible, avoid using auxiliary chemicals or solvents;
- Create Energy-Efficient Designs Energy consumption for synthesis should be kept to a minimum;

- Use of Renewable Feedstocks: Whenever feasible, feedstock should be renewable and depletion should be prevented;
- Minimize Derivatives Since blocking agents and protecting/deprotecting groups are the source of extra waste, they should be avoided whenever possible;
- Catalysis Compared to stoichiometric agents, catalysis agents are preferred;
- Chemicals must be designed for degradation so that, upon completion of synthesis, they decompose into non-toxic derivatives;
- Analysis in Real Time to Prevent Pollution Real-time monitoring of the synthesis is necessary to ensure that no harmful compounds are produced;
- To reduce the likelihood of hazardous mishaps, inherently safer chemicals for accident prevention agents employed in product synthesis should be chosen.

2. Dyes- A major group of Organic compound

Dyes are colorful organic chemicals that add color to a variety of materials, including food items, paper, leather, textiles, and polymers. They are categorized according to their source, ionic nature, application technique, and chemical structure. Since many dye classes have varied chemical characteristics, solubility, and environmental behavior, it is crucial to comprehend dye classification in order to choose the best wastewater treatment techniques. The chemical structure of azo, anthraquinone, triphenylmethane, xanthene, indigoid, and phthalocyanine colors determines their classification. About 60–70% of industrial dye production is made up of azo dyes, which make up the main group of these. They are widely used due to their bright colors and low production cost and have one or more azo (-N=N-) groups in their chemical structure. Anthraquinone dyes are known to have good color fastness and stability owing to the presence of anthraquinone rings in their structure. Triphenylmethane dyes like crystal violet and malachite green have strong color properties and excellent tinctorial strength. Dyes can be classified into mno-reactive, direct, vat, disperse, acid, basic, and sulfur based on the dyeing technique used. Reactive dyes form covalent bonds with textile fibers and they are extensively used in the cotton industry. Direct dyeing refers to the dyeing of fibers without any processing chemicals. Disperse dyes are used to dye synthetic fibers like polyester and vat dyes are insoluble in water and require a reduction process before their application.Basic dyes are used for both paper and acrylic fibers, whereas acid dyes are generally used for nylon, wool, and silk. Interestingly, mordant dyes are dependent on metal ions to adhere the color onto fabrics; sulfur dyes are suitable for dark shades and have excellent wash fastness qualities. There are three categories of dyes, which define the classification of the dyes: cationic, anionic, and non-ionic. Basic dyes belong to the cationic group, while acid dyes and the rest of the dye types (reactive and direct) belong to the category of anionic colors. This grouping is important as it is based on the affect of electrical charge on the process of adsorption and photocatalytic treatment. Therefore, creating effective treatment technologies and reducing environmental pollution require a grasp of dye classification (Robinson et al., 2001) Table 1.

Table 1- Types of Dyes and Major Application

Basis of Classification	Type of Dye	Characteristics	Common Examples	Major Applications
Chemical Structure	**Azo Dyes**	Contain one or more azo (-N=N-) groups; largest dye class	Methyl Orange, Congo Red	Textile, paper, leather
	Anthraquinone Dyes	Contain anthraquinone nucleus; excellent color fastness	Alizarin, Reactive Blue 19	Textile industry
	Triphenylmethane Dyes	Possess triphenylmethane structure; bright colors	Crystal Violet, Malachite Green	Paper, textile, biological staining
	Xanthene Dyes	Highly fluorescent dyes	Rhodamine B, Eosin Y	Cosmetics, printing, fluorescence studies
	Indigoid Dyes	Based on indigo structure	Indigo, Tyrian Purple	Denim and textile dyeing

	Phthalocyanine Dyes	Metal-containing macrocyclic compounds	Phthalocyanine Blue	Textile, paints, inks
Method of Application	**Reactive Dyes**	Form covalent bonds with fibers	Reactive Black 5, Reactive Blue 19	Cotton and cellulose fibers
	Direct Dyes	Applied directly without mordants	Congo Red, Direct Blue	Cotton, paper
	Acid Dyes	Applied in acidic medium	Acid Orange 7	Wool, silk, nylon
	Basic (Cationic) Dyes	Positively charged dyes	Methylene Blue, Crystal Violet	Acrylic fibers, paper
	Vat Dyes	Insoluble dyes reduced before application	Indigo	Cotton textiles
	Disperse Dyes	Slightly water-soluble dyes	Disperse Orange 3	Polyester and synthetic fibers
	Sulfur Dyes	Contain sulfur groups; economical	Sulfur Black 1	Cotton textiles
	Mordant Dyes	Require metal salts for fixation	Alizarin	Wool, leather
Ionic Nature	**Anionic Dyes**	Negatively charged in solution	Reactive, Acid, Direct Dyes	Textile dyeing
	Cationic Dyes	Positively charged in solution	Methylene Blue, Crystal Violet	Acrylic fibers, paper
	Non-Ionic Dyes	No ionic charge	Disperse Dyes	Synthetic fibers
Source	**Natural Dyes**	Derived from plants, animals, or minerals	Turmeric, Indigo, Henna	Textile, food coloring
	Synthetic Dyes	Chemically manufactured	Methylene Blue, Rhodamine B	Industrial applications

3. Metal oxide nanoparticle

Because of their superior physicochemical characteristics and wide variety of uses, One of the most important kinds of nanomaterials is metal oxide nanoparticles. Zinc oxide (ZnO), copper oxide (CuO), magnesium oxide (MgO), iron oxide (FeO_4), nickel oxide (NiO), cerium oxide, and titanium dioxide (TiO_2) (CeO_2) are among the metal oxide nanoparticles that are frequently investigated. High surface area, thermal stability, photocatalytic activity, antibacterial behavior, and adsorption efficiency are just a few of the outstanding characteristics displayed by these nanoparticles. Due to these features, they have found widespread application in fields such as catalysis, biomedical applications, environmental remediation, and sensing technologies. They have attracted large volumes of literature on their ability to eliminate organic pollutants and inhibit microbial growth (Klekotka et al., 2021).

4. Method of nanoparticle synthesis

Nanoparticles can be made via physical, chemical, and biological methods. Physical techniques such ball milling, evaporation-condensation, and laser ablation frequently call for costly machinery and high energy usage. Although they offer good control over particle size, chemical processes like hydrothermal, sol-gel, microemulsion, and chemical reduction techniques sometimes entail toxic reducing agents and dangerous compounds. Greener and more sustainable methods of producing nanoparticles have been developed as a result of the drawbacks of traditional synthesis methods (Gupta et al., 2023) .

4.1 Physical synthesis of nanoparticle

Physical methods of nanoparticle synthesis involve the production of nanoparticles through mechanical, thermal, or radiation-based processes without the direct use of chemical reducing agents. These methods generally choose either a bottom-up strategy, where nanoparticles are created by the condensation of vaporized atoms, or a top-down strategy, which breaks down bulk materials into nanosized particles. The exceptional purity, regulated crystallinity, and low chemical contamination of nanoparticles produced by physical synthesis methods make them popular. However, compared to biological (green) synthesis processes, these techniques are less cost-effective and environmentally sustainable because they typically call for costly equipment, significant

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energy usage, high temperatures, or vacuum conditions. Physical energy such as heat, laser light, electrical charge, mechanical force, and evaporation of the bulk material into nanoparticles are used in the physical synthesis of nanoparticles. The process parameters, such as temperature, pressure, and grinding time, affect the properties of the nanoparticles. Physical techniques, on the other hand, are known to produce high-quality nanoparticles, but at the disadvantage of high operating costs and limited scalability for standard laboratory applications (Nagime & Chandak, 2024) Figure 1. image it can be explain

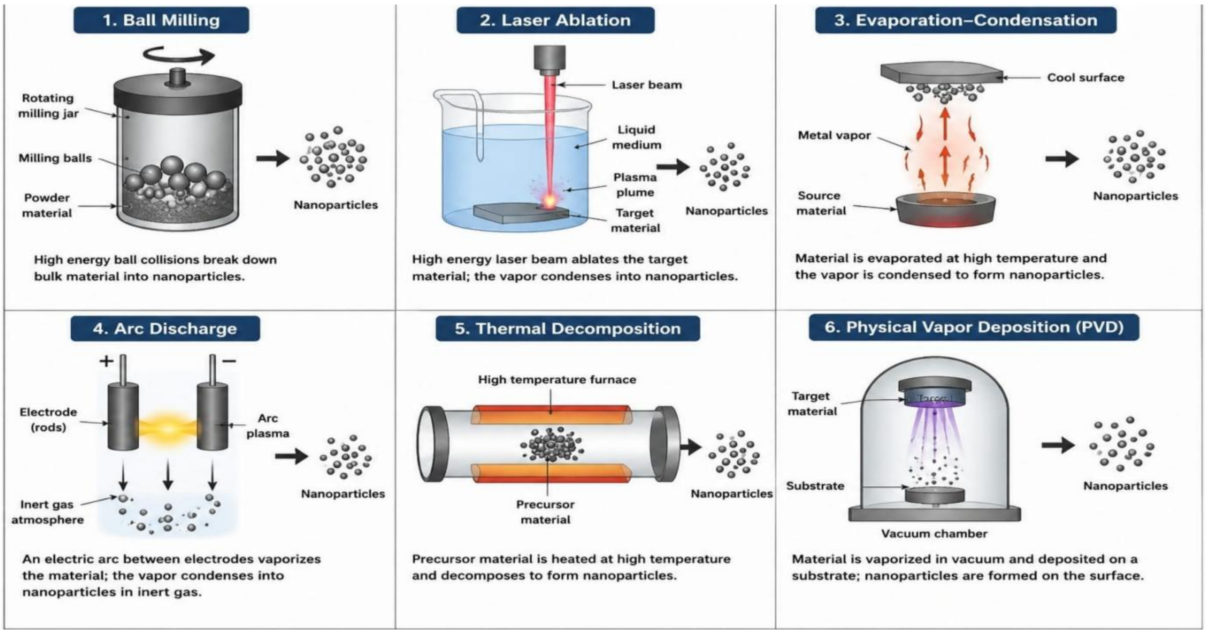

Figure 1 - Physical synthesis of nanoparticle

4.2 Chemical Synthesis of Nanoparticles

Chemical synthesis is one of the best-known techniques for producing nanoparticles since it gives good control over the size, shape, and composition of the particles. Nanoparticles are developed through chemical reactions where precursor compounds react in a solution. Chemical synthesis methods include chemical reduction, hydrothermal synthesis, co-precipitation, sol-gel synthesis, and microemulsion technique. In order to create metal nanoparticles, the chemical reduction process reduces metal salts using reducing agents such as citrate, hydrazine, and sodium borohydride. To reduce aggregation and regulate particle size, stabilizing agents or surfactants are applied. The hydrolysis and condensation process involving alkoxide or inorganic salts, which results in the development of a colloidal sol that eventually turns into a gel, is what defines the sol-gel technique. This is followed by the processes of calcination and drying, thus obtaining nanoparticles that are pure and homogeneous. Chemical synthesis methods are favored due to their simplicity, cost-effectiveness, scalability, and ability to produce nanoparticles with desired properties. However, these methods may require toxic chemicals and generate hazardous by-products, which can pose environmental and health concerns. Therefore, proper handling and disposal of chemicals are essential during nanoparticle synthesis (Szczyglewska et al., 2023) Figure 2.

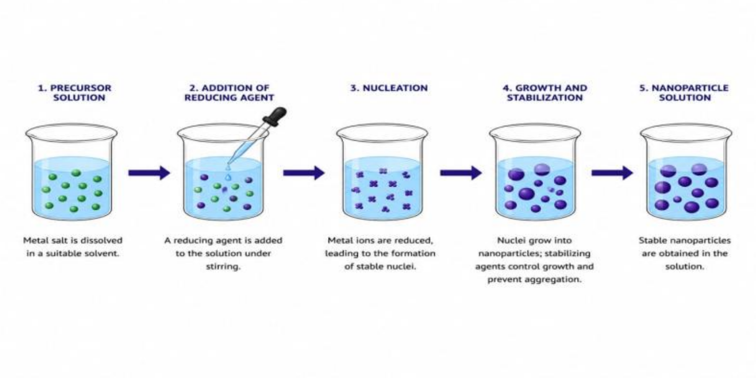

Figure 2- Chemical Synthesis of Nanoparticles

4.3 Green Synthesis of nanoparticle

Biogenic or "green synthesis" refers to the environmentally sustainable process of producing nanoparticles using biological systems such as plants, microorganisms and organic proteins. Plant-mediated synthesis is now gaining importance due to its simplicity, cost-effectiveness, speed and scalability. Plant extracts are rich in phytochemicals such as flavonoids, phenols, alkaloids, terpenoids, tannins and proteins that serve as biological reducing as well as stabilizing agents during the synthesis of nanoparticles. Through capping mechanisms, the biological molecules both inhibit aggregation and transform metal ions into nanoparticles. Reduced toxicity, fewer energy needs, eco-friendliness, improved biocompatibility, and cost-effectiveness are just a few benefits that green synthesis has over traditional techniques. As a result, one of the most active fields of nanotechnology research is biogenic synthesis (Ahmed et al., 2016) Figure .

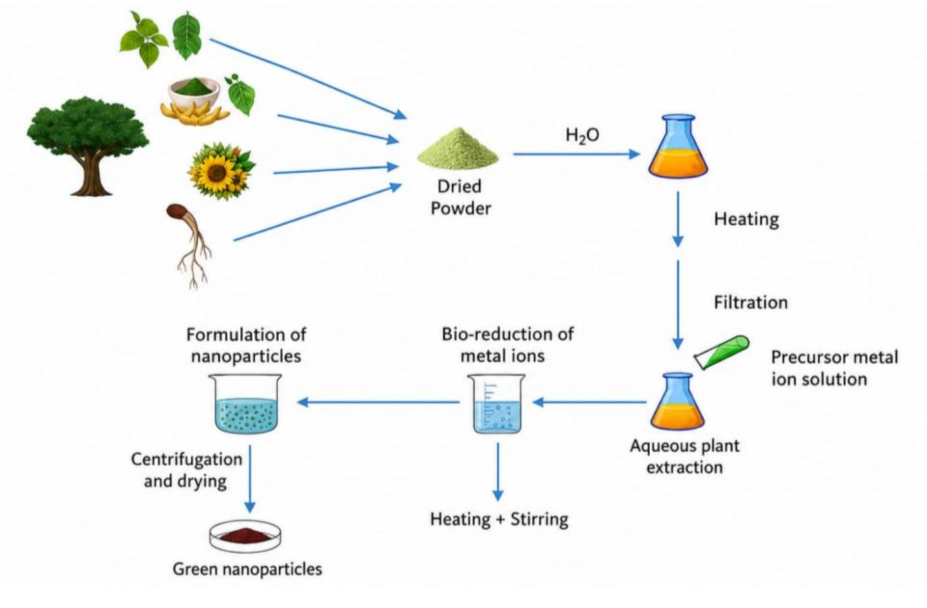

Figure 3 -Biological Green Synthesis of nanoparticle

4.4 Biological Sources for Green Synthesis

Plant Extracts

Plant-mediated synthesis is the most popular method because extracts are rich in phytochemicals capable of reducing metal ions and stabilizing nanoparticles. Leaves, roots, ruits, bark, flowers, and seeds of plants like Azadirachta indica, Ocimum sanctum, Aloe vera, Moringa oleifera, and Camellia sinensis are frequently used. Different plant parts, including the seed, fruit, callus, bark, stem, flowers, and leaves, are used in plant-mediated green synthesis processes to create metal and metal oxide nanoparticles of various sizes and shapes. Green chemistry approach to synthesize copper oxide nanoparticles (CuONPs) was reported using extracts from the root, stem, and leaves of the Macleaya cordata (Wild.) R.BR as reducing and stabilizing agents. Copper acetate precursor ($Cu(CH_3COO)_2$) was used for green synthesis of copper oxide nanoparticles through reduction and oxidation reactions (Zhu et al., 2024). Parthenium hysterophorus was extracted aqueously using the method described in Ref. 52, which involved dissolving 20 g of the plant sample in 200 mL of distilled water. The mixture was constantly stirred while being cooked to 40 °C for 45 minutes on a hot plate. Whatman No. 1 filter paper was used to filter the extract. After that, copper oxide nanoparticles were created using the extract. Copper (II) sulfate was used as a metal precursor in the synthesis of copper oxide nanoparticles. 1.59 g of CuSO4 was dissolved in 100 mL of distilled water to create a 0.01 M CuSO4 solution. A color shift and UV-Vis spectrophotometric measurement were used to track the creation of nanoparticles when the metal solution and parthenium aqueous extract were combined in a 1:4 ratio. The nanoparticles were dried in an oven at 80 °C after the colloidal solution was centrifuged for 15 minutes at 4000 rpm and repeatedly cleaned (Nzilu et al., 2023) Figure 1.

Microorganisms

Bacteria, fungi, and yeasts possess intrinsic metal-reducing enzymes that can convert metal precursors into nanoparticles. Bacillus, Pseudomonas, Aspergillus, and Fusarium species are commonly employed. Compared to chemical and physical approaches, the production of NPs from biological sources (bacteria, actinobacteria, yeast, fungi, algae, and viruses) is far safer. Since bacteria can be cultivated in artificial environments with an ambient growth rate, they are preferred over other microbes for the production of NPs. Through their extracellular or intracellular pathways, microbes can convert inorganic elements into nanoparticles (NPs) and adapt to greater metal concentrations. Microbes absorb metal ions from their surrounding environment/media and convert these metallic ions into elemental form via an enzymatic reduction (Koul et al., 2021). Numerous biomolecules derived from bacteria, including proteins, polysaccharides, and enzymes, can function as reducing agents to aid in the synthesis of NPs. The selection and isolation of bacteria is typically the first step in the manufacturing of iron oxide nanoparticles. This involves cultivating the strain on particular media, such as nutritional agar or BHI agar, and then incubating it It can also be necessary to have an atmosphere of carbon dioxide. Conditions such as a carbon dioxide atmosphere may also be required. After the individual colonies are obtained, they are placed in a nutritional medium, such as nutrient broth or Luria Bertani, and then they are centrifuged and incubated. The source from which the materials should be extracted will depend on the method employed for synthesis. The extraction will either come from the cell pellet (intracellular method) or the supernatant (extracellular method). Fungal biomass, cell-free filtrate (CFF), or fungal cell filtrate (FCF) can all be used to create metal nanoparticles. One of the easiest methods for producing nanoparticles is to use mycelium. Centrifugation is used to obtain mycelium once the appropriate fungal organism has grown in the chosen medium. After combining the acquired mycelium with the metal precursor salt solution, it is incubated at 28 °C for four to five days. The mixture is then filtered to produce colloidal nanoparticles (Zúñiga-Miranda et al., 2023).

Algae and Cyanobacteria

The synthesis of metal and metal oxide nanoparticles has been carried out using algae as a green method of fabrication. Unlike bacteria-based techniques, algae do not go through the processes of cellular maintenance. Algae are a rich source of phytochemicals in the production of metal nanoparticles (Chaudhary et al., 2020). In contrast, cyanobacteria and microalgae have attracted attention for green synthesis because of their hyperaccumulation of heavy metals, increased CO2 fixation rate, absence of toxic waste, and their ability to utilize biomolecules (pigments and enzymes) as reducing agents. Marine and freshwater algae are rich in polysaccharides, pigments, and proteins that aid in metal ion reduction and nanoparticle stabilization. This makes them a significant bio-manufacturer for nanoparticle production (Radulescu et al., 2023).

Agricultural and Industrial Waste

There are numerous potential uses for green-synthesized MtNPs in agriculture to boost agricultural output. Products including nanopesticides, nanofungicides, nanobiosensors, and nanofertilizers are frequently produced using MtNPs. These nano-based products can help increase the quality and yield of agricultural products, reduce chemical pollution or even protect crops from environmental pressuresFruit peels, vegetable waste, sugarcane

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bagasse, rice husk, tea waste, and brewery waste provide an inexpensive resource for nanoparticle synthesis while promoting waste valorization (Bahrulolum et al., 2021) figure 4.

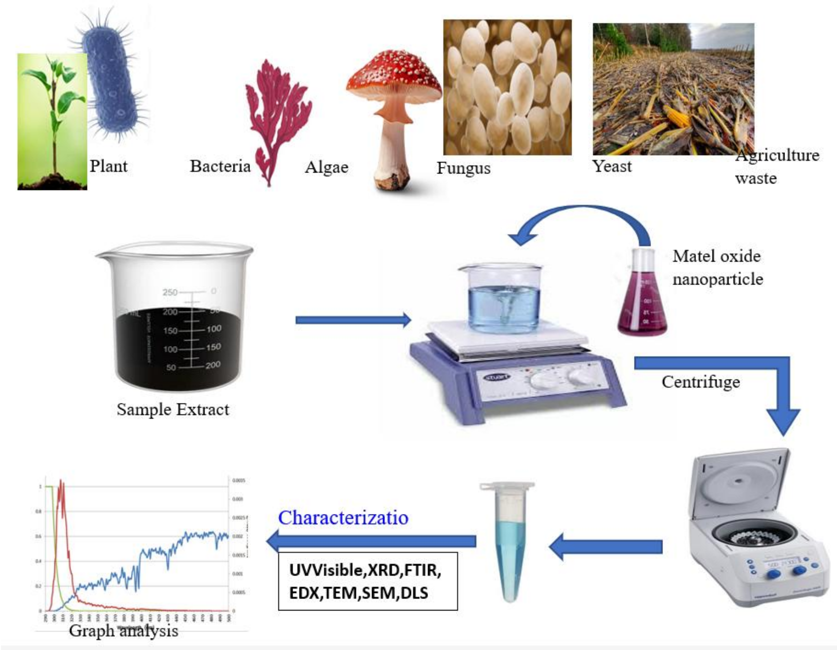

Figure 4: Method for green synthesis metal oxide nanoparticle

5. Application of metal oxide nanoparticle

Synthetic dyes from textile, leather, paper, and printing industries are among the most frequent water contaminants. They are often toxic, carcinogenic, and resistant to conventional biological treatment because of their complex aromatic structures. Metal oxide nanoparticles (MO-NPs) have become one of the leading materials for removing these dyes because of their high surface area, tunable band gaps, chemical stability, and low cost. Two main mechanisms are used:

- **Adsorption** — dye molecules bind to the nanoparticle surface via electrostatic attraction, hydrogen bonding, or complexation.
- **Photocatalytic degradation** — light excites electrons in the nanoparticle, generating reactive oxygen species (ROS) that break down the dye into smaller, less harmful molecules (ideally CO_2 and H_2O).

Table 2: Dye removal with different metal oxide nanoparticle

Nanoparticle	Band Gap (eV)	Key Strengths	Typical Dyes Treated
TiO_2 (Titanium dioxide)	~3.2	Most studied photocatalyst, chemically stable, non-toxic	Methylene blue, Rhodamine B, Congo red
ZnO (Zinc oxide)	~3.3	High electron mobility, low-cost synthesis	Methylene blue, Malachite green
Fe_3O_4 / γ-Fe_2O_3 (Iron oxides)	~2.0	Magnetically separable, Fenton-like activity	Reactive dyes, azo dyes
CuO (Copper oxide)	~1.2–1.7	Visible-light active, antibacterial	Methyl orange, Eosin
SnO_2 (Tin oxide)	~3.6	Good stability, often used in composites	Methylene blue, Rhodamine B
NiO (Nickel oxide)	~3.6–4.0	p-type semiconductor, good with heterojunctions	Various azo dyes
MnO_2 (Manganese oxide)	~1.3	Strong oxidizing ability, adsorption capacity	Methylene blue, Crystal violet

3. Mechanism of Photocatalytic Dye Degradation

1. **Photon absorption**: UV or visible light with energy ≥ band gap excites an electron from the conduction band (CB) to the valence band (VB), forming an electron–hole pair (e^-/h^+).
2. Charge separation and migration: Holes and electrons move to the surface of the nanoparticle.
3. Production of reactive oxygen species (ROS):

- $h^+ + H_2O \rightarrow \bullet OH + H^+$
- $e^- + O_2 \rightarrow \bullet O_2^-$

1. **Dye degradation**: $\bullet OH$ and $\bullet O_2^-$ radicals attack the chromophore groups (e.g., azo bonds, aromatic rings) of the dye, breaking them into intermediates and eventually mineralizing them to CO_2, H_2O, and inorganic ions.
2. **Recombination loss**: A major step that limits efficiency is the recombination of e^- and h^+ before reaching the surface, which prevents degradation from occurring. For this purpose, doping materials, heterojunctions, and composites are utilized.

Table 3: Factors Affecting Removal Efficiency

Factor	Effect
pH	Alters surface charge of NP and ionization state of dye; affects adsorption/degradation rate
Catalyst dosage	Having a larger amount will promote more active sites but if excessive amount are used ,then may be light scattering or turbidity.
Initial dye concentration	Higher concentration may saturate active sites which may lead to a decrease in , degradation.
Light intensity/source	Whether ultra violet or visible light is used influences which nanoparticle become active.
Temperature	In general increasing reaction rate will allow for an optimum level of reaction beyond which desorption can take place.
Presence of ions/organic matter	Competing for active sites or scavenging of reactive oxygen species may occur.

4. Conclusion:

Metal oxide nanoparticles have emerged as highly promising multifunctional nanomaterials for both environmental remediation and biomedical applications. Their high surface area, tunable physicochemical properties, excellent catalytic efficiency, and ease of surface functionalization make them effective agents for the adsorption and photocatalytic degradation of textile dyes, contributing to sustainable wastewater treatment. Simultaneously, these nanoparticles exhibit significant anticancer potential through mechanisms such as reactive oxygen species generation, targeted drug delivery, apoptosis induction, and selective cytotoxicity toward cancer cells. Despite these encouraging outcomes, challenges related to biocompatibility, long-term toxicity, environmental fate, scalability, and clinical translation remain to be addressed. Future research should focus on developing green synthesis approaches, improving nanoparticle stability and targeting efficiency, and conducting comprehensive in vivo and clinical investigations. With continued advancements in nanotechnology, metal oxide nanoparticles are expected to play a pivotal role in advancing sustainable environmental management and next-generation cancer therapeutics, bridging the gap between laboratory research and practical real-world applications.

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