



A Review on Green Synthesis of Magnetic Nanoparticles: Unlocking Catalytic Potential for Environmental Sustainability

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Abstract: Eco-friendly nanomaterials have garnered a lot of attention recently because of their long-term benefits across a range of industrial domains. Traditional techniques for creating nanoparticles frequently require a lot of energy and hazardous chemicals, both of which pollute the environment. The primary objective of this work is on recent developments in the environmentally friendly synthesis of magnetic nanoparticles, particularly those made of iron oxide (FeO), copper oxide (CuO), and nickel oxide (NiO). By utilizing natural resources including plant extracts, microorganisms, and agricultural waste, green synthesis provides an alternate technique. This technique enhances the nanoparticles' catalytic activity while simultaneously promoting environmental safety. Their significance in sustainable technologies is emphasized in this review, particularly in applications like as pollution control, redox processes, and carbon dioxide reduction. The synthesis methods, catalytic efficiency and environmental relevance of these green-synthesized nanoparticles are discussed. Such approaches support sustainable nanotechnology. The knowledge about green synthesis methods is vital for producing efficient and safer nanomaterials. As industries shift towards eco-conscious production, these materials may find wide application in future technologies.

Keywords: Magnetic nanoparticles, Green Synthesis, Photocatalyst, CuO, Sustainability

1. Introduction

The need for sustainable nanomaterials has increased dramatically as a result of the rapid growth of cities and enterprises. A United Nations assessment projects that the global market for nanotechnology will reach USD 125 billion by 2024, mostly as a result of its growing applications in the sectors of electronics, healthcare, and the environment [1]. However, traditional approaches to the synthesis of nanoparticles rely on hazardous chemicals, require a lot of energy, and produce a lot of trash. Both human health and the environment are at risk from these behaviours. They also cause soil and water contamination and increase the carbon footprint [2]. In fields including hydrogen production, wastewater treatment, electronics, energy storage, sensors and medicine, nanotechnology is still crucial [3]. In energy systems, nanoparticles help in

increasing the surface area of electrodes in microbial fuel cells. This enhances electron movement and improves power output. They are also used in proton exchange membranes, which help in better proton conduction and minimize oxygen leakage between electrodes [4].

In the fuel sector, both metal and non-metal nanoparticles support better combustion of biodiesel. This reduces greenhouse gases and air pollution. They also help in reducing wear and tear, managing carbon layers and lowering engine maintenance costs, thus improving engine life [5, 6]. Nanocatalysts also play a role in converting biomass to biofuels. Recent studies show that these catalysts use lesser amounts than traditional ones but give higher bio-oil yield. Their efficiency is due to larger surface area, better redox features and more active reaction sites [7, 8]. These

advancements encourage the adoption of safer and more environmentally friendly materials. The two most common methods for creating nanoparticles are top-down and bottom-up. These techniques frequently make use of physical or chemical processes. They use hazardous solvents and reducing chemicals, despite the fact that they enable mass production in less time. These substances have the potential to damage ecosystems and cause health problems. The need for safer, environmentally friendly techniques has grown as a result of these worries. A solution with less harm to the environment is provided by green nanotechnology [9]. By avoiding hazardous reagents, this method seeks to produce beneficial nanomaterials. Although it is still in its infancy, this field has a lot of potential. Green-synthesized nanoparticles typically exhibit enhanced features and increased safety. Among various nanomaterials, metal oxide nanoparticles like CuO are widely used in catalysis, energy storage, nanofluids, medical research, pollution sensing and organic transformation [10–19]. Their synthesis can be done through different methods such as chemical vapor deposition [20], sol-gel [21], liquid-phase synthesis [22], electrodeposition [23] and colloidal

techniques [24]. However, many of these techniques involve harmful chemicals, take long reaction time, and follow complex steps. They also leave behind chemical waste and toxic by-products, which raise environmental concerns [25]. These drawbacks stress the need for green and safer approaches to produce CuO and other similar nanoparticles.

In recent years, nanoparticles have become more widely used in commerce. Their safety for the environment and their health has also come into question. By employing natural resources to create nanoparticles in a more environmentally responsible manner, green nanotechnology offers an alternate path [26, 27]. This process eliminates the need for hazardous chemicals. It takes a sustainable and safe route. Figure 1 illustrates the fundamental concept of green nanotechnology. Green synthesis has gained a lot of attention as a result of these urgent issues. This method employs agricultural waste, microbes and plant parts as stabilizing and reducing agents [28]. It promotes the principles of green chemistry and provides a means of lessening the negative impacts of conventional synthesis.

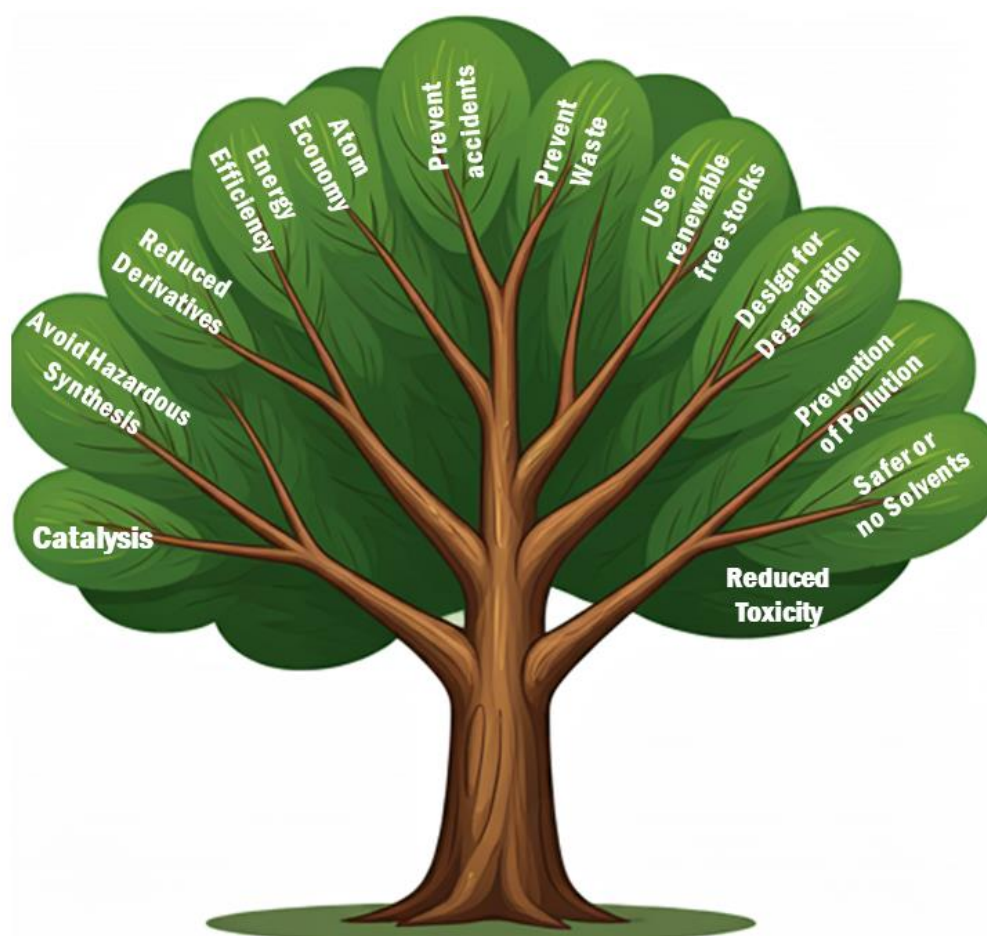


Figure 1. The major principles of green technology



This review focuses on the recent progress in making magnetic nanoparticles using ecofriendly methods. Iron oxide (FeO), copper oxide (CuO) and nickel oxide (NiO) are of special interest. These particles are gaining attention because of their large surface area, good magnetic response, and high catalytic efficiency [29]. They are seen as useful materials for both industrial and environmental uses. The synthesis techniques, benefits, and catalytic roles of FeO, CuO and NiO are explained in this article. Their role in meeting sustainable goals is also underlined. As industries and researchers adopt eco-conscious methods, green synthesis becomes more important. This paper provides insight into how these magnetic nanoparticles can help solve environmental problems when produced through green routes [30].

2. Magnetic Nanomaterials – An Overview

Magnetic nanoparticles (MNPs) are materials with size usually between 1 and 100 nanometers. At this size, their magnetic behavior changes because of size limitation. These particles are mostly made from magnetic metals like iron (Fe), cobalt (Co), nickel (Ni) and their oxides such as FeO, Fe₂O₃, Fe₃O₄, CuO and NiO [31]. Among them, iron oxide, copper oxide and nickel oxide are the most studied. These materials are used in different areas including energy systems, catalysis, medical applications and environmental cleanup. Their magnetic nature, stability and surface reactivity make them suitable for such wide usage.

2.1 Key Characteristics

2.1.1 Magnetic Properties

The high surface-to-volume ratio of magnetic nanoparticles, which results from their small size, is one of their most significant characteristics. Because of this characteristic, there are more active sites, which improves their ability to interact with nearby molecules [32]. This results in more effective reactions in catalytic processes. MNPs show ferromagnetic, ferrimagnetic or superparamagnetic magnetism depending on their size. When exposed to an external magnetic field, nanoparticles smaller than 20–30 nm usually become superparamagnetic, which means they lose their magnetization when the field is removed [33]. This keeps the particles from clumping together and qualifies them for biomedical applications like MRI imaging and medication administration. On the other hand, bigger nanoparticles do not require a field to

maintain their magnetization. In environmental applications, this ferromagnetic or ferrimagnetic property is useful for pollution separation [34].

2.1.2 Optical and Electronic Properties

Additionally, magnetic nanoparticles exhibit distinct electrical and optical properties, particularly as their size reduces. Quantum effects alter their ability to conduct electricity or absorb light at the nanoscale. For example, Iron oxide nanoparticles are helpful in photo catalysis and pollution control because they absorb particular light wavelengths. These size-related effects [32] support their function in chemical and environmental processes. Magnetic anisotropy, in which the magnetic behaviour varies with direction, is another significant characteristic. The structure and form of particle have an impact on its directional character. This is advantageous in applications like magnetic data storage. Higher anisotropy ensures the particles maintain a stable orientation over time.

2.1.3 Surface Functionalization and Biocompatibility

Different coatings or chemical groups can be added to magnetic nanoparticles to modify their surface. They are suitable for particular applications because to this functionalization, particularly in the medical domain. Their safety and interaction with biological systems can be enhanced by coatings such as ligands or biopolymers. By enhancing their dispersion, it also aids in avoiding particle clumping in liquid solutions. In the absence of such alterations, magnetic and molecular forces frequently cause nanoparticles to adhere to one another, decreasing their reactivity. Stabilizers like polymers or surfactants are employed to prevent this. These contribute to the uniform distribution of water and other solutions, which is critical for applications such as catalysis, imaging and water purification [35].

2.1.4 Chemical Stability and Oxidation Resistance

Iron-based magnetic nanoparticles such FeO₄ and FeO₃ are susceptible to oxidation in air, which gradually reduces their magnetic properties [36]. Protective coatings like silica, carbon, or polymer layers are applied to increase their durability. Even under challenging circumstances, as those encountered during wastewater treatment or catalytic processes, these coatings aid in preserving their functionality. The



capacity of magnetic nanoparticles to produce heat in the presence of alternating magnetic fields makes them valuable as well. This characteristic is used in the cancer therapy technique known as magnetic hyperthermia. They are appropriate for localized thermal therapies because of their small size, which permits rapid heat release. Magnetic nanoparticles help in biological and catalytic areas. This is because they can chemically interact with different molecules. This is especially true when their surface has specific functions for particular uses. Magnetic nanoparticles are useful materials in many fields. They have high surface reactivity, special magnetic behaviour and a very small size. Their features can change with surface treatment and how they are made. This makes them good for applications in chemical processes, environmental technology and healthcare [37]. These features make magnetic nanoparticles a good type of material. They help create efficient and eco-friendly technology.

2.2 Applications of Magnetic Nanoparticles

MNPs or magnetic nanoparticles exhibit unique properties. These characteristics attract a lot of interest. They make applications in numerous industries possible. They are suitable for applications due to their tiny size, magnetic behaviour and ease of functionalization. These include medical care, pollution prevention, and energy systems. The relationship between these characteristics and practical applications across many industries is depicted in Figure 2.

2.2.1 Biomedical Applications

In contemporary medicine, magnetic nanoparticles are crucial, particularly in fields like cancer treatment, drug delivery and imaging. They are perfect for precision treatments because of their small size and superparamagnetic nature. One of the primary applications is in drug delivery systems. Here, medications are affixed to nanoparticles and guided by an external magnetic field to particular bodily parts. This reduces adverse effects and increases treatment accuracy. In cancer treatment, such targeted administration is very beneficial because it guarantees that the medication only effects the tumor and leaves healthy tissues unaffected. The biocompatibility and ease of surface modification of iron oxide (FeO_4) make it stand out among the materials employed [38].

Green-synthesised copper oxide nanoparticles, those made with *Parthenium hysterophorus*, provide an economical and ecologically safe means of combating pollution while preserving sustainability [39]. Superparamagnetic iron oxide nanoparticles or SPIONs are frequently employed as MRI contrast agents in medical imaging. These particles help make pictures clear. They also aid in finding tumors, inflammation or vascular diseases more accurately. They accomplish this by shortening the T2 relaxation time of adjacent water protons. Another novel application of MNPs in the treatment of cancer is magnetic hyperthermia. These particles generate heat when they enter tumors and are exposed to an alternating magnetic field.

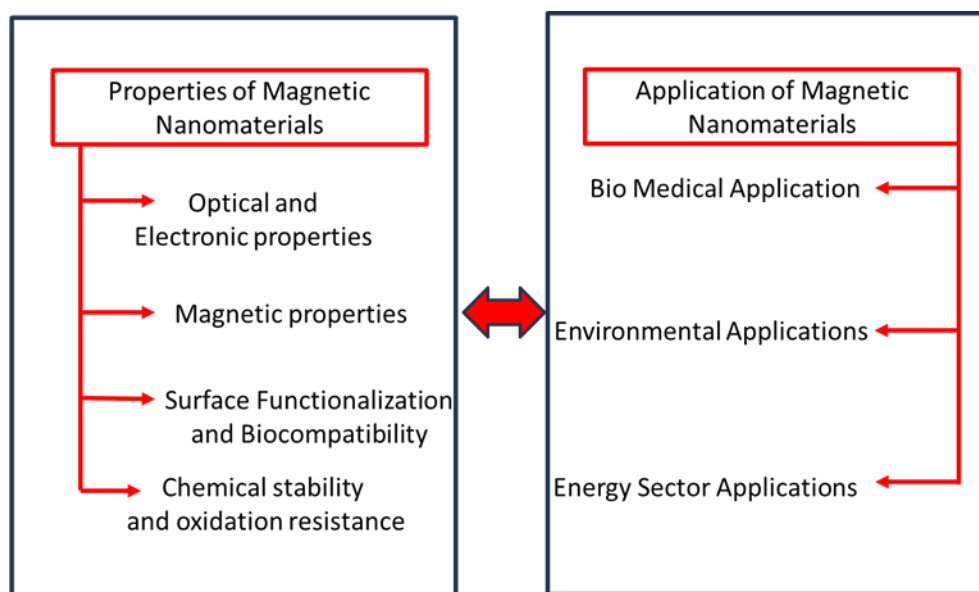


Figure 2. The relationship between properties and applications of magnetic nanomaterials



This heat aids in the destruction of cancerous cells. The surrounding healthy tissues are unaffected [40]. For such little medical operations, they are ideal. This is due to their controlled ability to generate heat in a particular location. Biosensors are another application for MNPs.

In diagnostics, these biosensors aid in the detection of biomolecules. Only target molecules can be adhered to by these particles. Pathogens, proteins and toxins are a few examples. This happens when the particles have a coating of enzymes or antibodies. Their magnetic nature makes it possible for them to detect these things in a sensitive and quick way. This helps both environmental checks and medical diagnosis.

2.2.2 Environmental Applications

Magnetic nanoparticles show promise in cleaning up contaminated soil and water. Their ability to react, large surface area, and magnetic response help remove many harmful materials. Iron oxide nanoparticles, such as FeO_4 and FeO_3 , often find use in water filter systems. They successfully remove heavy metals from wastewater. These include lead, chromium and arsenic [41, 42]. Once these particles absorb the contaminants, a magnet can easily take them out. This allows for reuse and less waste. It is possible to change these particles to target specific pollutants. This involves adding suitable chemical groups to their surface. This makes them work better and adjust to different environmental conditions. Also, iron oxide and copper oxide nanoparticles act as photocatalysts. They help break down organic pollutants. These include common wastewater substances like dyes, insecticides and medicine residues. The particles initiate breakdown reactions when exposed to light. They can be separated for reuse using a magnet after treatment [43]. MNPs are used in soil cleanup to get rid of dangerous metals and organic pollutants. They are good for use in the field. This is because they can absorb and hold contaminants. Also, it is easy to recover them with a magnet. Zero-valent iron nanoparticles (nZVI) are often used to break down dangerous substances. These include PCBs and TCEs found in groundwater and soil. Additionally, magnetic nanoparticles help clean up oil spills. Iron oxide particles covered with water-repelling compounds can collect oil from water surfaces. Magnets then take out these particles once they are full of oil. This gives a clean and effective way to deal with spills [44].

2.2.3 Energy Sector Applications

Magnetic nanoparticles additionally support energy technologies. Lithium-ion batteries (LIBs) employ FeO_4 and NiO nanoparticles as electrode materials. Their large surface area and electron movement improve charge-discharge cycles and battery capacity. Specifically, NiO particles have a long work life and strong reversible capacity. This makes them useful in future batteries [45]. Their magnetic properties give electrodes more mechanical strength. This makes batteries last longer and perform better. Platinum-based magnetic nanocomposites find use as catalysts in fuel cells. This is especially true for proton-exchange membrane (PEM) types. These substances help make important reactions go faster. Examples include oxygen reduction and hydrogen oxidation [46]. This increases the energy conversion efficiency of the cell. By boosting power density, they make fuel cells better for uses at a fixed location and in portable devices. Supercapacitors also use magnetic nanoparticles as active materials. Their magnetic features help electrons move faster. This makes charge and discharge rates better. Their very large surface area allows for much energy storage. So, they are perfect for power systems that need high capacity and quick energy delivery.

Iron and copper oxides are used in catalysis for energy-producing processes. This includes making hydrogen from water splitting and biofuel from biomass. Their magnetic properties and surface activity support their catalytic work. These nanoparticles are easy to separate and reuse. This boosts their importance in sustainable energy applications. Magnetic nanoparticles have promising applications in many important fields.

They support diagnostic tools and targeted treatments in the medical field. They aid in the removal of harmful materials from soil and water, which lowers pollution in environmental activities [47-48]. In the energy sector, they facilitate effective catalysis, extend battery life and enhance fuel cell performance. Their range of applications is anticipated to grow as synthesis and surface engineering research advances, addressing important issues in energy systems, sustainability and medicine.

3. Synthesis of Magnetic Nanomaterials

Numerous synthesis processes have been developed in response to the increasing demand for magnetic nanoparticles across many industries.



Figure 3. The various synthesis methods of magnetic nanomaterials

Depending on the requirements of the application, these techniques seek to regulate the size, shape, and composition of the particles. The main synthesis techniques for creating magnetic nanoparticles are shown in Figure 3. Chemical processes, such as co-precipitation, sol-gel, hydrothermal, and polyol, rely on reactions in solution. Although they may use hazardous chemicals, these provide greater control over particle characteristics. On the other hand, physical procedures including vapor deposition and ball milling rely on heat or mechanical energy. These techniques are effective for producing particles with precise sizes. However, they often consume significant amounts of energy. Furthermore, they can lead to negative environmental consequences. Sustainability factors and the necessary material attributes determine which approach is best. It is anticipated that future developments would concentrate on effective and environmentally sustainable substitutes for creating these materials.

3.1 Conventional Physical Methods

Physical methods have historically been used to generate magnetic nanoparticles, especially where great crystallinity and uniform particle size are required. However, the environment may be harmed

by these practices. They often use a lot of energy too. Two popular methods are ball milling and vapor deposition. The advantages and disadvantages of each will be discussed in the following sections.

3.1.1 Ball Milling

Ball milling is a mechanical way to make nanoparticles from bigger materials. In this process, the material goes inside a turning chamber. This chamber has hard balls made of ceramic or steel. As the chamber turns, the balls hit the material again and again. This breaks the material into smaller pieces. Forces like hitting and rubbing make this size reduction happen. This method often makes nickel oxide (NiO) and iron oxide (FeO_4 , FeO_3) nanoparticles. These materials find use in catalysis and water clean-up. This is because they can absorb things and have magnetic features [49, 50]. For example, FeO_3 nanoparticles made by ball milling can take out pollutants from water. A magnet can then easily separate them. Ball milling is a cheap method. It works well to make large amounts of nanoparticles. It is beneficial for industrial applications because it is scalable as well. By altering variables like the milling time, ball-to-powder ratio or rotating speed, the final particle size can be changed. For applications where size affects performance, this



degree of control is crucial. Ball milling uses a lot of energy despite its advantages. The procedure is expensive because of the continual power needed for the movement and collisions inside the chamber. Impurities may be added to the product over time as a result of milling equipment wear and tear. In fields where purity is crucial, like biomedicine, this could be an issue. Furthermore, the procedure is not in line with green chemistry principles, and it can have a substantial negative impact on the environment particularly when used extensively [51].

3.1.2 Vapor Deposition Techniques

In order to create a thin layer of nanoparticles, materials from a vapor phase are deposited onto a surface via vapor deposition. Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD) are its two main categories.

3.1.2.1 Physical Vapor Deposition (PVD)

The substance intended for deposit is first converted to vapor using PVD. For this, it makes use of energy sources like heat or plasma. When this vapor hits a solid surface, a thin layer of nanoparticles is created. This process aids in the creation of metal films. Iron, nickel and cobalt are a few examples. It provides good control over the thickness and size of particles. For electronics and magnetic storage devices, this is crucial. In a vacuum, PVD takes place. This indicates that the likelihood of dirt or undesired items is low. Thus, it can produce materials for sensors and medical equipment. However, PVD needs high temperatures to turn solids into vapor. Also, it uses complex vacuum systems. This makes operating costs and energy use higher. These limits restrict its use in large-scale production. From an environment point, PVD is not a sustainable technology [51]. This is due to its high energy needs and it does not work with green processes.

3.1.2.2 Chemical Vapor Deposition (CVD)

CVD makes thin films or nanoparticles. It does this through chemical reactions. These reactions happen between gas reactants and a surface. Materials like FeO_4 , FeO_3 and NiO are frequently synthesized using this method for applications in electronics, storage devices and catalytic systems [53]. Because of their stable magnetic characteristics, FeO_4 nanoparticles produced by CVD are used in systems such as magnetoresistive random-access memory

(MRAM). Catalytic processes and sensors both employ NiO nanoparticles made by CVD. CVD can produce homogenous, high-purity nanoparticles with consistent structural characteristics, which are essential for advanced electrical and magnetic applications. Additionally, it facilitates the application of different chemical precursors, giving material designers more freedom that is creative. However, the production of hazardous byproducts during chemical reactions is one of the main issues in CVD. These byproducts can have an adverse effect on worker safety and the environment if they are not properly controlled. Like PVD, the process requires high temperatures and vacuum systems, which makes it less ecologically friendly and energy-intensive.

3.1.3 Drawbacks and Environmental Impact of Conventional Physical Methods

Despite being efficient, vapor deposition and ball milling have significant disadvantages. Ball milling uses mechanical grind. Vapor deposition needs high temperature and vacuum systems. Both of these methods need a lot of energy. This makes them less suitable for sustainability. This is especially true when compared to new green synthesis methods. During ball milling, worn-out machinery can release unwanted materials. This might affect the product quality. Chemical reactions in vapor deposition can create dangerous byproducts. This brings up more safety and environment concerns. These difficulties show that future studies must use cleaner and more effective synthesis ways. These issues matter a lot. Industries and researchers now focus more on eco-friendly ways to make things. Traditional physical methods need much energy and have environment risks. So, there is more interest in other, more sustainable ways to make magnetic nanomaterials. Techniques like green synthesis are becoming popular. These use biological agents or renewable resources. They give similar results but harm the environment less [28]. Changing to greener synthesis methods will be very important for future nanomaterial creation. This is especially true for industries focused on environment sustainability.

3.2 Chemical Synthesis Methods

Chemical synthesis methods for magnetic nanomaterials are very common. This is because they are flexible. They can also make nanoparticles with exact control over size, shape and crystal structure. These methods often involve chemical reactions in a solution. This allows for adding different functional

groups or coatings. These additions make the nanoparticles work better for specific uses. Many chemical methods have become popular for making magnetic nanoparticles. This is because they can be scaled up and are flexible. The most effective ones are sol-gel, hydrothermal and co-precipitation techniques. Each method has its own good points. However, there are also drawbacks. These include problems with process control, safety, and environment.

3.2.1 Co-Precipitation Method

The co-precipitation method is one of the simplest and most popular ways to make magnetic nanoparticles. This process involves adding a base to a water-based solution. This causes metal hydroxides to form, usually from iron salts. When water is present, these hydroxides then change into metal oxides. This method often makes iron oxide nanoparticles, such as FeO₄ and FeO₃. These find use in medical imaging and environment clean-up [53]. This method is easy to use. It can make many nanoparticles without needing costly equipment. Also, the size and shape of the final particles can be precisely controlled. This happens by changing things like temperature, reactant amount, and pH. This level of control is very important when specific features are needed. For example, magnetism or catalysis are needed for particular uses. However, dangerous substances often find use in the co-precipitation process [54]. These include ammonia and sodium hydroxide. If not handled correctly, these substances can harm the environment and human health. A low level of crystal structure in the particles can be a problem. This feature may negatively affect how well they work overall. To make their structure stronger in some cases, heat treatment after making them might be needed.

3.2.2 Sol-Gel Method

The sol-gel method is a common way to make magnetic nanoparticles. It makes it possible to manage composition and size. First, there is a sol. There are metal beginning elements in this liquid mixture. Through hydrolysis and condensation reactions, it slowly turns into a gel. Metal oxide nanoparticles form once the gel dries and gets heat. This method can make particles with a large surface area and many pores. These are useful in catalytic and sensor applications. For instance, FeO₄ nanoparticles made with this method are often used in thin film coatings for electronics and in environment repair work. The sol-gel method is known for making pure nanoparticles

that are all the same. It also gives precise control over the final product's structure and chemical make-up [55]. This technology still uses harmful materials. This is true even though it usually works at lower temperatures than vapor-based methods. Organic liquids used in the process can harm the environment if not thrown away properly. Also, metal alkoxides used as starting materials are often dangerous and react easily. In addition, the gel might shrink or break during the heat and dry processes. This could lower the final product's quality.

3.2.3 Hydrothermal and Solvothermal Methods

Hydrothermal synthesis uses water as the solvent. It happens at high temperatures and pressures inside a sealed container. Instead, organic solvents are used in the related solvothermal process. Both methods are employed to create uniformly sized, well-defined, highly crystalline magnetic nanoparticles. In this manner, materials like FeO₄, CuO and NiO are frequently produced. By modifying variables like reaction time, pressure and temperature, these techniques enable exact control over the characteristics of the particles. Applications for this control include energy storage, environmental treatment and catalysis. Compared to other processes that use hazardous solvents, hydrothermal synthesis is more ecofriendly because water is frequently used as the solvent [56]. Despite their benefits, these techniques demand a lot of energy because of the harsh autoclave conditions. The requirement for specialized equipment raises operating costs and restricts large-scale utilization. The use of organic solvents in solvothermal synthesis may present safety and environmental hazards. Nevertheless, these techniques are frequently employed to create nanoparticles for catalytic systems, fuel cells and batteries. For example, hydrothermally produced FeO₄ nanoparticles have been effectively employed in lithium-ion batteries due to their stability and energy-storage capabilities [57].

3.2.4 Compression Process

Bulk materials are broken down into nanoparticles by mechanical force in the compression process, also known as mechanical or high-energy ball milling. This technique involves putting powdered materials into a revolving chamber with hard balls, often composed of ceramic or steel. Through impact and friction, the action reduces particle size by causing the balls and powder to collide repeatedly [58]. This process works well for industrial production of



magnetic nanoparticles such as NiO and FeO₄. Changing the milling time, speed and ball-to-powder ratio makes it easy to control the particle size and shape. This method is cheap for large-scale production. The equipment needed is not too expensive. FeO₄ nanoparticles made with this technique show good results. They help remove dyes and heavy metals from wastewater. This is due to their surface reactivity and magnetic features.

3.2.5 Polyol Method

The polyol method makes metal and metal oxide nanoparticles. It uses polyol molecules like ethylene glycol as a reducer and solvent [59]. In this process, metal salts get heat and dissolve in the polyol. As the solution gets hotter, the metal ions inside it reduce. This creates nanoparticles. The polyol helps stabilize these nanoparticles.

This stops them from sticking together. This method offers good control over particle size and shape. This is useful in catalytic and electrical uses. Also, it uses less energy. This is because it works at lower temperatures compared to other chemical processes. By changing the metal salts and reaction conditions, many types of nanoparticles can be made. Examples include FeO, CuO and NiO. While NiO nanoparticles are utilized in energy systems such as batteries and supercapacitors because of their potent electrochemical performance, CuO nanoparticles produced using this technique have demonstrated good results in degrading toxins in water [60, 61].

3.2.6 Environmental and Safety Concerns in Chemical Methods

Chemical synthesis techniques frequently use hazardous reagents and solvents, although offering great flexibility and control over nanoparticle properties. Both the environment and human health are at risk from substances like metal alkoxides and organic solvents. Pollution may result from improper handling of the trash from these procedures. Furthermore, some methods like solvothermal and hydrothermal synthesis take a lot of energy because to the high temperature and pressure requirements [62].

Though methods like co-precipitation, sol-gel and hydrothermal synthesis have proven effective in producing magnetic nanoparticles with specific features, their environmental footprint remains a concern. As sustainability becomes a growing priority, there is a clear need to shift towards cleaner and more

environment-friendly alternatives that minimize toxicity and reduce energy use.

3.3 Introduction to Green Synthesis

Green synthesis is now very popular. This is because traditional ways to make magnetic nanomaterials cause more and more environment and health problems. Green synthesis means using more sustainable processes. It is an environment-friendly way to make nanoparticles, especially magnetic nanoparticles (MNPs). It uses biological agents like bacteria, plant extracts, and other natural materials. This approach follows the rules of green chemistry. It removes or greatly cuts down on the use of dangerous chemicals, harmful solvents, and energy-heavy methods. This section will talk about green synthesis. It will cover its methods and its growing importance for sustainability. Green synthesis is a group of eco-friendly techniques. These techniques use renewable resources or biological systems to create nanoparticles. It puts a lot of focus on less waste, less energy use, and less hazardous material use [63]. Green synthesis builds on natural processes. This makes it safer and more sustainable than old chemical and physical ways. The green synthesis of magnetic nanoparticles can be achieved using a variety of biological agents. Various parts of plants, such as leaves, roots, fruits and seeds, contain bioactive compounds (e.g., alkaloids, flavonoids, terpenoids, phenolics) that can act as reducing and stabilizing agents during nanoparticle formation. Bacteria, fungi, and algae can reduce metal ions to nanoparticles through enzymatic or non-enzymatic processes. These biological agents offer a natural, renewable source for nanoparticle synthesis. Proteins, polysaccharides and other biomolecules extracted from natural sources can be used to mediate the formation of nanoparticles, providing both reducing power and stability. Figure 4 shows the steps involved in the green synthesis process. This approach builds on the principles of green chemistry. These principles stress the design of processes that limit energy use. They also use renewable starting materials. They further reduce or remove the use and creation of harmful compounds.

3.3.1 Relevance of Green Synthesis for Sustainability

The need for more environment-friendly ways to make nanomaterials has grown. This led to a rise in the importance of green synthesis in recent years.

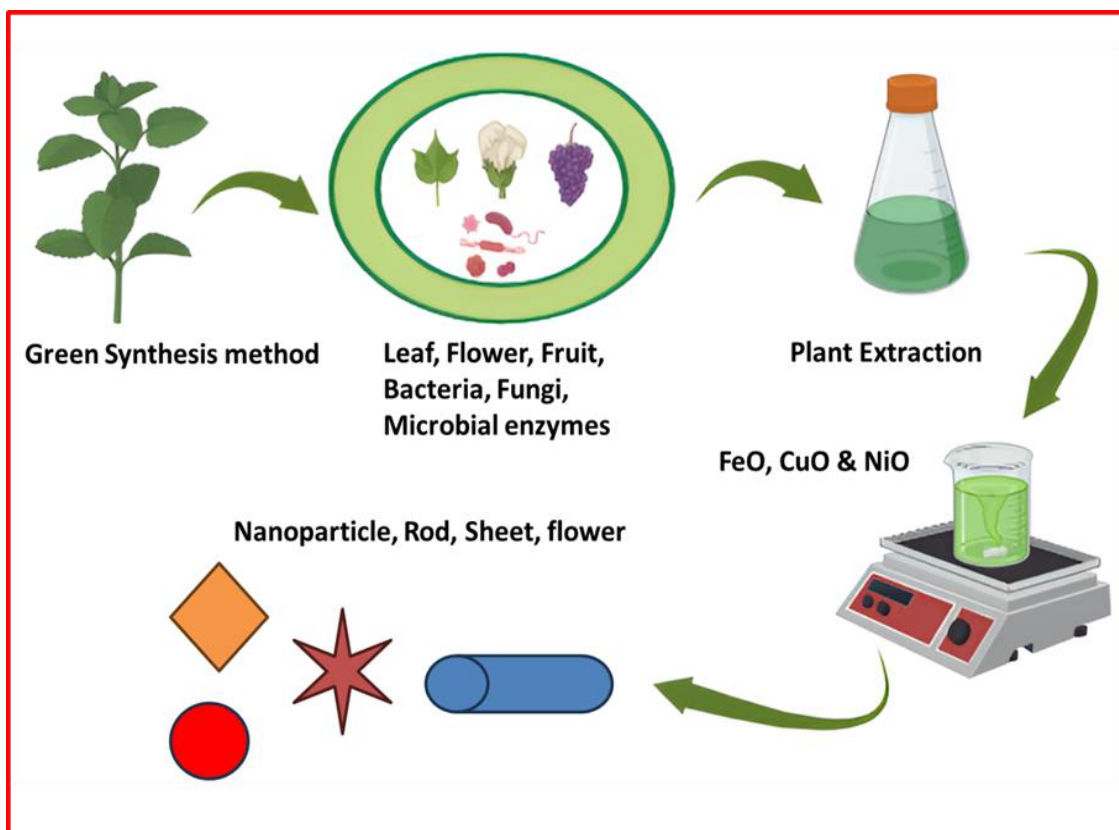


Figure 4. The process involved in green synthesis process

Traditional methods for making nanoparticles often use harmful solvents, poisonous chemicals and a lot of energy. All of these can negatively affect the environment and human health. Green synthesis, however, offers a safer and more sustainable choice. It removes the need for dangerous materials. Examples include strong acids, bases, and organic solvents. These often find use in chemical processes like co-precipitation and sol-gel. Green synthesis uses natural things like plant extracts instead of artificial chemicals. These natural items are renewable, non-toxic and break down easily. For example, iron oxide nanoparticles (FeO_4) made from orange peel extract (*Citrus sinensis*) show excellent catalytic activity without needing harmful chemicals [64].

Green synthesis often happens in gentle conditions. This means it often occurs at room temperature and normal air pressure. This is different from physical processes like ball milling or vapor deposition. These need high temperatures, pressures, or mechanical force. As a result, less energy is used. Operating costs also go down. An excellent example is using extracts from aloe vera or neem. This makes nanoparticles without needing high temperatures. Green synthesis also helps a circular economy. It turns waste into useful nanomaterials. It does this by using microbial cultures or biological waste as raw materials.

For instance, rice husks and banana peels helped create copper oxide (CuO) nanoparticles [65]. This not only uses sustainable bioreducers but also helps with waste management. These methods usually make nanoparticles that are compatible with living things. This makes them good for sensitive uses. These include biosensors, imaging, and medicine delivery. No harmful remains make them safer for use in medicine and the environment. For example, iron oxide nanoparticles made from *Moringa oleifera* leaves show high compatibility with biological systems. This makes them a possible choice for targeted medicine delivery and MRI imaging. Furthermore, green synthesis based on plants is straightforward, affordable and simple to scale up. Green solutions are appropriate for wider adoption especially in resource-limited contexts because they can be implemented with minimum resources unlike traditional chemical treatments that may require extensive infrastructure or specialized skills.

3.3.2 Methods

3.3.2.1 Plant-Mediated Synthesis

The most popular green synthesis methods are those based on plants. Phenolics, alkaloids and terpenoids compounds abundant in plants act as



capping and reducing agents in the natural process of nanoparticle production. Typically, plant extracts are combined with metal salts, including those that contain iron. The extract of active ingredients generates nanoparticles by reducing the metal ions. The same plant-based chemicals then stabilize them, enhancing their stability and avoiding clumping. For example, it has been discovered that iron oxide nanoparticles made from the leaf extract of neem (*Azadirachta indica*) are efficient at decomposing pollutants. This eco-friendly and simple procedure eliminates the need for dangerous chemicals entirely [66].

3.3.2.2 Microbial Synthesis

Microorganisms such as fungi and bacteria also provide a natural method of producing nanoparticles. These microorganisms use their metabolic or enzymatic processes to transform metal ions into nanoparticles. Controlling the size and shape of the final particles, which are regulated by the biological environment, is one benefit of microbial synthesis. For example, FeO₄ nanoparticles made by *Pseudomonas aeruginosa* have demonstrated good efficacy in water purification because of their huge surface area and magnetic activity [64].

3.3.2.3 Synthesis Using Biomolecules

Green synthesis can also make use of biomolecules such as polysaccharides, proteins and peptides. These molecules provide locations for further surface modifications while also stabilizing the nanoparticles and lowering metal ions. In biomedical applications, where tailored distribution or improved cell interaction are required, this property is quite helpful. For example, nickel oxide (NiO) nanoparticles synthesized from proteins have demonstrated encouraging catalytic activity in hydrogen evolution processes (HER), which qualifies them for application in energy systems such as fuel cells [67].

4. Synthesis of FeO, CuO and NiO Nanoparticles

4.1 Iron Oxide Nanoparticles

Iron oxide nanoparticles, such as FeO, FeO₃, and FeO₄, are being researched extensively due of their many uses in fields such as medication delivery, environmental remediation, magnetic storage and catalysis. Traditional techniques for creating these nanoparticles frequently involve the use of harsh

chemicals, high-energy consumption, and the discharge of dangerous byproducts into the environment [38, 68, 69]. Green synthesis methods have surfaced as a cleaner solution to these issues. These methods use natural resources such biodegradable polymers, algae, and plant extracts. They promote the use of renewable resources, reduce energy use and stay away from hazardous chemicals.

4.1.1 Plant-Based Synthesis of FeO Nanoparticles

Numerous active substances including phenolics, flavonoids, alkaloids and terpenoids are found in plants. These substances can lower metal ions and aid in stabilizing the nanoparticles as they are forming. Plant extracts are the most common green synthesis method. This is due to their ease of use, low cost and environment-friendly nature. FeO nanoparticles, in many sizes and shapes, have been successfully made from plant leaves, roots, fruits, and flowers. Neem (*Azadirachta indica*) leaves have many terpenoids and polyphenols. These substances act as organic reducers. They change iron salts into nanoparticles [66]. This method does not need harmful chemicals like sodium borohydride and hydrazine. Neem-derived FeO₄ nanoparticles show good results. They effectively remove contaminants and dyes. This makes them suitable for use in environment clean-up. Hibiscus flowers contain anthocyanins. These act as stabilizers and reducers during nanoparticle creation [70]. The nanoparticles formed are biocompatible and non-toxic. This is very important for medical uses. FeO₃ nanoparticles from hibiscus extract show antibacterial qualities. They can be used in medical coatings and for medicine delivery. Similarly, green tea extract has polyphenols and catechins. This makes it a good material for FeO₃ production. Green tea-derived nanoparticles have good crystal structure and strong magnetic activity. This makes them valuable for uses like magnetic hyperthermia in cancer treatment and MRI imaging.

4.1.2 Microorganisms-Mediated Synthesis of FeO Nanoparticles

Algae, both large and small, can also make iron oxide nanoparticles. These organisms have hydroxyl, amino and carboxyl functional groups. These groups can reduce iron salts. They also help stabilize the nanoparticles that form. Algae-based synthesis helps large-scale production. It needs few resources and has less impact on the environment.

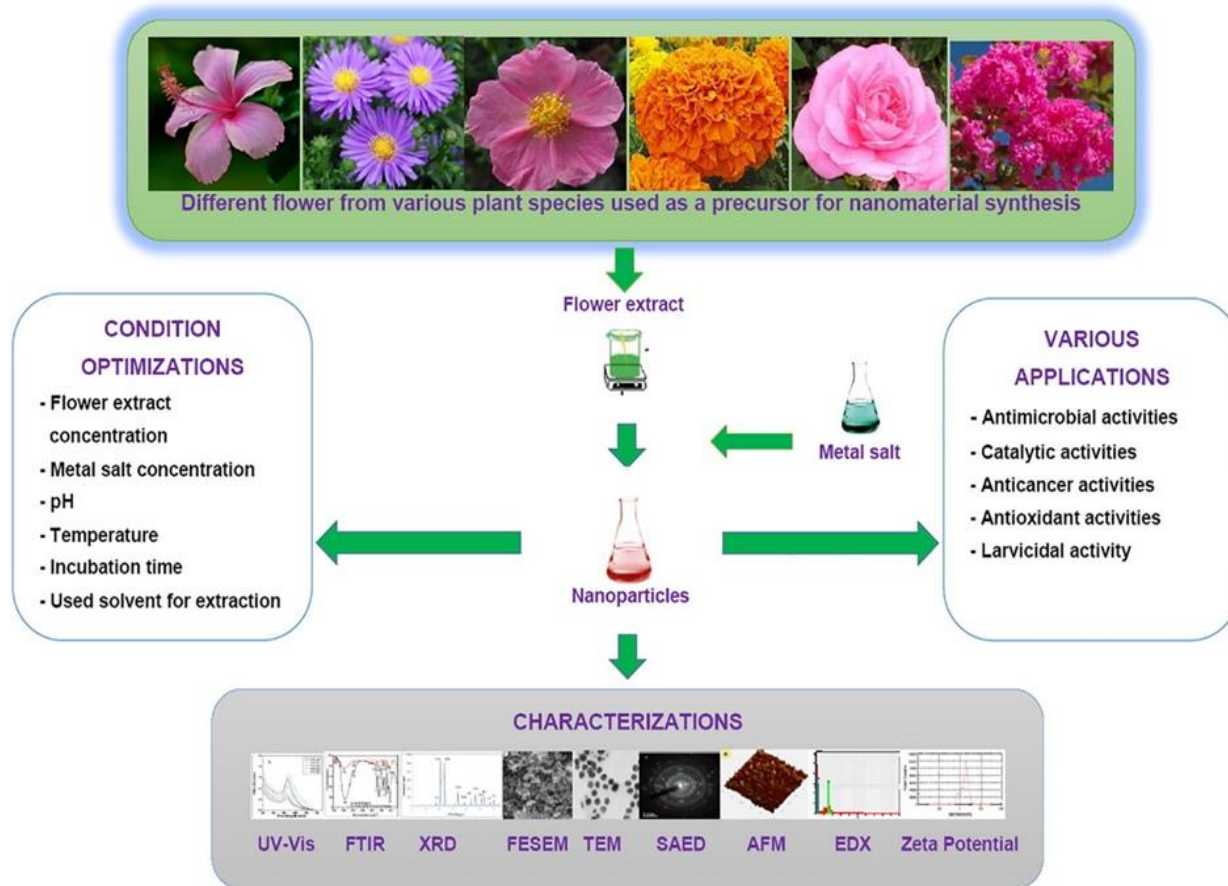


Figure 5. Flower-mediated nanoparticles fabrication, characterization and their applications [70].

Chlorella vulgaris and other microalgae show an ability to reduce metal ions in water-based solutions. This leads to FeO₄ nanoparticles [64]. These particles are useful for magnetic separation and wastewater treatment. Algae can grow easily in large amounts. They grow fast and only need simple things like water and sunlight. So, algae-based synthesis is good for industrial application. Generally, the nanoparticles made are safe for environment and medical uses.

4.1.3 Biopolymer-Assisted Synthesis of FeO Nanoparticles

The creation of nanoparticles also involves natural polymers. These include cellulose, chitosan, and starch. These biopolymers are good choices instead of chemical agents. They are non-toxic and renewable. They help keep the nanoparticles stable. They also help reduce iron salts. Chitosan, a polymer from crab shells, has amino and hydroxyl groups. These help with stability and reduction. Chitosan-based FeO nanoparticles spread easily in water. This is important for uses like medicine delivery and pollution prevention. Starch is another helpful polymer for green synthesis. It is easy to get, breaks down naturally, and

has hydroxyl groups. These groups help reduce iron salts. They also stop the nanoparticles from sticking together. FeO₃ nanoparticles from starch show effectiveness in breaking down contaminants using light. This shows their promise for environment repair [71].

4.1.4 Advantages of Ecofriendly Synthesis for FeO Nanoparticles

Green synthesis of FeO nanoparticles offers several benefits over traditional chemical or physical methods. It greatly cuts down on the use of dangerous materials and energy. This makes the entire process safer and more eco-friendly. Unlike traditional methods like vapor deposition or hydrothermal treatment, which need high heat and pressure, methods using plant extracts or algae can happen in gentle conditions at room temperature. Toxic chemicals are replaced by natural substances found in plants and algae, such as alkaloids and flavonoids, which reduce environmental risks. Natural ingredients are used in green synthesis; therefore, the resulting nanoparticles are often safe for biological usage. This qualifies them for use in medical domains such as cancer treatment, drug delivery, and MRI. Green-synthesised nanoparticles are more



biocompatible than chemically produced ones since they do not contain any traces of harmful components [64]. Another consideration is cost; materials derived from plants and algae are frequently inexpensive and easy to find. Additionally, these methods are simpler to scale up, which contributes to the increasing industrial need for magnetic nanoparticles.

Standardizing these procedures for large-scale production still presents difficulties, despite the obvious advantages. The goal of future studies should be to improve the efficiency and consistency of synthesis particularly when scaling up. The procedure will also be improved by investigating fresh biological sources and learning more about the mechanisms underlying these natural agents. All things considered, FeO nanoparticles produced from plants, algae, and natural polymers exhibit a lot of potential for use in fields including health, pollution prevention, and catalysis. With more advancements, green synthesis is probably going to be the go-to technique for producing ecofriendly magnetic nanoparticles.

4.2 CuO Nanoparticles

The broad range of applications for copper oxide nanoparticles (CuO NPs) in fields such as antibacterial treatments, energy storage, environmental cleanup and catalysis has drawn interest. Traditional production methods frequently use powerful chemicals and a lot of energy, which can be harmful to the environment and human health. Green synthesis techniques, on the other hand, offer a cleaner choice. These processes use natural and renewable resources. Examples include fruit peels, vegetable extracts and farm waste. These eco-friendly methods use less energy. They also make fewer harmful byproducts. This makes them better for large-scale, sustainable uses.

4.2.1 Fruit Peel-Based Synthesis

Fruit peels are often seen as waste. Yet, they have many flavonoids, polyphenols and organic acids. These organic materials work well as stabilizers and reducers when nanoparticles form. Using fruit peels helps reduce waste. It also gives a cheap way to make nanoparticles. Orange peels have flavonoids, polyphenols and citric acid. They have been used much to make CuO nanoparticles. This process uses the active substances in the peel extract. These substances change copper salts into CuO nanoparticles. The method that results is easy to use. It uses less energy.

It also makes nanoparticles that are very good at speeding up the breakdown of organic pollutants. CuO nanoparticles from orange peels show strong action. They break down dyes and other pollutants found in wastewater. CuO nanoparticles have also been successfully made from banana peels. Banana peels are well-known for their high potassium and antioxidant content [72]. These particles are good for use in medicine and the environment. This is because of their strong antibacterial and light-activated breakdown properties. Also, the process helps turn farm waste into useful material.

4.2.2 Vegetable Extract-Based Synthesis

Vegetable extracts are another helpful source. They have organic antioxidants and active ingredients. This help to make nanoparticles. These extracts not only lower copper salts. They also make the nanoparticles that form more stable. This often removes the need for artificial coating agents. For example, spinach leaves have oxalic acid, flavonoids, and ascorbic acid. These help with both reduction and stability during synthesis. CuO nanoparticles from spinach extract show consistent particle size and better light-activated breakdown. This is especially true for removing antibiotic and other medicine residues from water. Tomato extracts, rich in Vitamin C and lycopene, are also useful for making CuO nanoparticles in an eco-friendly way [73]. This process makes nanoparticles with strong antibacterial properties. They are good for the environment and fit for use in medical equipment and water clean-up. This method is more practical for industrial uses. This is because using tomato extract further lowers production costs.

4.2.3 Synthesis from Agricultural Waste

Husks, plant waste and peels are examples of agricultural waste. They provide an unused and sustainable resource for making nanoparticles. These materials have many active substances. These can help reduce copper salts into CuO nanoparticles. For example, rice husks have many organic acids and silica. They have been successfully used for this purpose. The method gives a low-cost, renewable source for making nanoparticles. It also helps reduce waste. CuO nanoparticles made with rice husk extract show excellent catalytic activity. This is for removing colours and heavy metals from wastewater [74]. Similarly, sugarcane bagasse is what is left after juice extraction. It has cellulose, lignin, and hemicellulose. These substances work as reducers. They help form



CuO nanoparticles. These nanoparticles are very good at breaking down pollutants. Using sugarcane waste promotes the circular use of farm byproducts. It also makes things more sustainable.

4.2.4 Benefits of Eco-Friendly CuO Nanoparticle Synthesis

Green production of CuO nanoparticles offers various benefits over standard chemical ways. A main advantage is how easy and cheap the process is. This is especially true when using plant-based or farm products. These methods are good for industrial use. This is because they use less energy and often work in mild conditions. Applications include catalysis, antibacterial solutions, and wastewater treatment [75]. Another important benefit is no toxic substances or solvents. Natural reducers from fruits, vegetables, and farm waste make the method safer for both people and the environment. Green synthesis further lessens its environmental impact by making fewer harmful byproducts. Materials that would otherwise be thrown away gain value. They turn into a resource from farm waste [76]. This approach supports sustainable actions and better use of resources. It fits well with the idea of a circular economy. Furthermore, most green synthesis methods use less energy. They often work at normal temperature and pressure. This makes them eco-friendly and cost-effective over time.

The eco-friendly synthesis procedures for CuO nanoparticles offer a practical choice to old ways. They reduce environmental harm. They also support large-scale production. These methods boost resource efficiency and lower pollution. They do this by using natural and renewable resources. Examples include fruit peels, vegetable extracts, and farm waste. More research can look into new biological sources. It can also make these methods more consistent. Green synthesis is expected to be vital in making high-performance CuO nanoparticles. This is for uses in energy systems, healthcare, and environmental protection. This is as businesses aim for more sustainable development.

4.3 NiO Nanoparticles

Nickel oxide (NiO) nanoparticles have many uses. These include electrochemical sensors, energy storage, supercapacitors and catalysis. Their strong catalytic activity, excellent optical features and high heat stability make them popular. Old ways to make NiO nanoparticles need much energy. They also often

use harmful chemicals. This brings up questions about environmental damage and safety. Green synthesis offers a better choice. This method uses biological sources. These include bacteria, fungi and organic waste. It does not use dangerous chemicals. It also uses less energy. This section explains several eco-friendly ways to make NiO nanoparticles. It highlights their benefits for sustainable production.

4.3.1 Fungi-Based Synthesis

The ability of fungi to reduce metal ions through enzyme action makes them useful for NiO nanoparticle synthesis. They contain organic compounds, proteins, and enzymes. This help change nickel salts into nanoparticles [77]. Fungi are easy to grow. This is one of their main benefits. It makes large-scale production more possible. Nanoparticles from fungi are also generally safe for use in environment and medical applications. The low cost and use of simple nutrient medium to grow the fungi further boost their potential for large-scale production. *Aspergillus niger* is a fungus often studied. It has been used successfully to make NiO nanoparticles. Some enzymes found in its extract effectively reduce nickel ions. This synthesis method is seen as sustainable. This is due to its low energy needs and avoidance of dangerous chemicals. Nanoparticles from *Aspergillus niger* show excellent ability to break down contaminants. These include dyes and insecticides. This makes them valuable for environment repair [67].

4.3.2 Bacteria-Based Synthesis

Some bacteria, like fungus, can naturally reduce metal salts. They do this using their proteins and enzymes. In bacteria-assisted synthesis, bacterial metabolism affects the change of nickel salts into nanoparticles. The size and shape of the nanoparticles can be controlled. This happens by picking the right bacterial strains and changing how they grow. This method is safe for the environment. It also gives more control over the quality of the final product. *Pseudomonas aeruginosa* is one such bacterium. It is well-known for its strong reducing ability [78]. NiO nanoparticles with good catalytic and electrochemical features have been successfully made using it. Devices like supercapacitors and electrochemical sensors might use these nanoparticles. The method is both affordable and renewable. This is because bacteria can be grown on a big scale at a low cost. Also, this method supports safer production and less environmental impact. It removes the need for dangerous chemicals.



4.3.3 Biowaste-Based Synthesis

Plant leftovers, peels and natural fibers are examples of organic waste from industry and agriculture. They have useful parts that can be used to make nanoparticles. This method helps cut waste. It also offers a sustainable and cheap source of reducers. Sugarcane bagasse is the pulp left after juice extraction. It has many natural proteins, carbs and acids [79]. These parts help reduce nickel salts to NiO nanoparticles. This method has made nanoparticles with good catalytic strength. This is especially true for treating dirty water. Similarly, coconut shell extract has flavonoids and tannins. It has been a green source for NiO nanoparticles. Supercapacitors and other energy storage devices can use the coconut shell-derived nanoparticles. This is because they have strong electrochemical activity [28]. These biowaste-based methods lessen the load of farm waste. They also economically turn it into valuable nanomaterials. This makes them good for industrial growth.

4.3.4 Use of Natural Fiber Templates

NiO nanoparticles form using natural fibers. These include chitosan and cellulose as templates. These substances help make nanoparticles of uniform size and shape. They act as structural guides and reducers. By using fewer man-made chemicals, these templates also support cleaner synthesis. Cellulose, a polymer from plants, has hydroxyl groups. This help reduce metal ions. Its fibrous structure guides the formation of nanoparticles. High surface area and porosity NiO nanoparticles are the end result, and these are very helpful in catalytic and energy storage processes. Similar applications have also been made of chitosan, a substance that is derived from crab shells [80]. It offers mechanical support during the production of nanoparticles in addition to aiding in the reduction of nickel ions. Because of their great adsorption capability, the NiO nanoparticles produced with chitosan are stable and safe for use in water purification, particularly for eliminating contaminants and heavy metals.

4.3.5 Advantages of Green Synthesis for NiO Nanoparticles

Eco-friendly synthesis techniques are superior to conventional chemical procedures in many ways. They are safer for the environment and human health because, above all, they avoid or employ less harmful chemicals and solvents [47]. Utilizing natural agents like bacteria, fungi and agricultural waste promotes

safer handling and disposal while lowering hazardous byproducts. These green technologies frequently operate in mild circumstances such as room temperature and pressure resulting in energy savings over high-temperature processes such as hydrothermal or vapor deposition. The fact that the basic materials natural fibers, biowaste and plant waste are readily available and reasonably priced makes them economical as well. This qualifies the techniques for the large-scale manufacturing of NiO nanoparticles, which are employed in a number of applications such as energy storage, water treatment and catalysis. In comparison to traditional methods, green production of NiO nanoparticles provides a safer, more affordable and cleaner alternative. It lessens the overall impact on the environment by using biodegradable and renewable resources. Future studies should focus on enhancing these methods' scalability and dependability. Additional prospects for the manufacture of sustainable nanoparticles may arise from the discovery of new biological sources. Green synthesis is expected to be a crucial technique in creating high-quality NiO nanoparticles for real-world uses in energy and environmental fields as attention shifts toward more ecofriendly technology.

5. Comparison and Discussion

Green synthesis of magnetic nanoparticles, particularly FeO, CuO and NiO, provides important information about sustainable practices, eco-friendly methods and catalytic performance. The catalytic efficiency of these nanoparticles is increased and environmental objectives are met when natural sources including plant extracts, microorganisms and agricultural waste are used in synthesis procedures. This section contrasts each nanoparticle's catalytic performance, sustainability, ease of manufacture and synthesis methods. The comparison of FeO, CuO and NiO nanoparticles produced using ecofriendly techniques is shown in Table 1.

Green methods of synthesizing nanoparticles minimize their influence on the environment by utilizing easily accessible biological resources. Bioactive substances found in plant extracts operate as stabilizing and reducing agents. Plant-based nanoparticle synthesis is a cost-effective and easily scalable approach. FeO and CuO nanoparticles made from orange peels and neem leaves, for example, have demonstrated exceptional catalytic activity [81]. Microbial pathways, such as the application of fungi and bacteria, are also successful.

**Table 1.** FeO, CuO, and NiO Nanoparticles with Green Synthesis Methods

Nanoparticle	Green Synthesis Method	Catalytic Activity	Environmental Benefits	Reference
FeO	Plant Extract (Aegle marmelos)	Photocatalytic activity for the reduction of Basic Fuchsin Dye	sustainable method, eco-friendly, no harmful by-products	[68]
FeO	<i>Anastatica hierochuntica</i>	catalytic activity of hydroxyl radical	Non-toxic, eco-friendly approach	[81]
Fe ₃ O ₄	Aloe vera extract	Degradation of organic pollutants	Biocompatible, non-toxic precursors	[38]
Fe ₂ O ₃	Orange peel extract	Photocatalytic degradation of organic pollutants	Renewable and abundant resource for bioreductant	[69]
Fe ₃ O ₄	Green tea extract	Detection of hydrogen peroxide	Biocompatible, readily available precursor	[82]
α -Fe ₂ O ₃	Hibiscus sabdariffa extract	Antibacterial activity	Non-toxic, eco-friendly approach	[83]
Fe ₃ O ₄	Neem leaf extract	Degradation of dyes and pharmaceuticals	Renewable resource, eliminates hazardous chemicals	[66]
Fe ₂ O ₃	Potato peel extract	Photocatalytic degradation of organic pollutants	Waste valorization, avoids toxic chemicals	[84]
α -Fe ₂ O ₃	Fresh green tea leaves	photocatalytic activity of hydroxyl radical	Biocompatible, eliminates hazardous chemicals	[85]
α -Fe ₂ O ₃	<i>Psoralea corylifolia</i> seeds	catalytic activity on methylene blue and Anticancer Activity	Non-toxic, eco-friendly approach	[86]
Fe ₂ O ₃	<i>leaves, stems, bark, flowers, seed fruits</i>	Degradation of pharmaceuticals, dyes, pesticides and heavy metals	Biocompatible, eliminates hazardous chemicals	[87]
Fe ₂ O ₃	<i>Amla</i>	catalyst for the effective removal of toxic dyes	Renewable resource, eliminates hazardous chemicals	[88]
Fe ₃ O ₄	Citrus sinensis peel extract	Degradation of organic pollutants	Waste valorization, readily available precursor	[41]
Fe ₂ O ₃	Moringa oleifera leaf extract	Photocatalytic degradation of organic pollutants	Economical, readily available precursor	[89]
Fe ₂ O ₃	Carica papaya leaf	photocatalytic degradation of remazol yellow RR dye and antibacterial activity	Biocompatible, eliminates toxic chemicals	[90]
Fe ₂ O ₃	<i>Ocimum sanctum</i> leaf extract	Anti-microbial activity	Biocompatible, eliminates toxic chemicals	[42]



CuO	<i>Parthenium hysterophorus</i>	degradation of rifampicin antibiotic	remediation of environmental pollution from antibiotics	[39]
CuO	<i>Curcuma longa</i>	excellent antioxidant and anti-Alzheimer's agents	nonhazardous and biocompatible nature	[76]
CuO	<i>Aerva javanica</i> Leaf	Antimicrobial and Cytotoxic Activities	biocompatibility	[91]
CuO	<i>Eucalyptus Globoulus leaf</i>	photocatalytic degradation of dye (Methyl Orange)	Biocompatible, eliminates toxic chemicals	[43]
CuO	<i>Celastrus paniculatus Willd. leaf</i>	Photocatalytic degradation of organic dye methylene blue	Biocompatible, eliminates toxic chemicals	[74]
CuO	Prunus amygdalus pericarp	bioactive compounds	bioreduction green approach	[92]
CuO	<i>Seriphidium oliverianum</i>	degradation of water-soluble industrial dyes	Biocompatible, eliminates toxic chemicals	[93]
CuO	<i>Eupatorium odoratum</i> and <i>Acanthospermum hispidum</i> leaf	Antibacterial Effects Against Pathogens	bioreduction green approach	[94]
CuO	<i>Ephedra Alata plant</i>	destruction of pathogenic bacteria, the degradation of dyes	bioremediation of industrial and domestic waste	[75]
CuO	extract of <i>Brassica oleracea var. italic</i>	antifungal activity against <i>Aspergillus niger</i> and <i>Candida Albicans</i>	Bioreduction, green approach	[95]
CuO	<i>Bacopa monnieri</i> leaf	potential antibacterial, anti-diabetic, and anti-inflammatory agent	ecofriendly approach	[76]
CuO	<i>Lantana camara</i>	catalytic activity towards the aza-Michael reaction	bioremediation of industrial and domestic waste	[96]
NiO	<i>Calotropis gigantea</i>	antibiotic abilities	ecofriendly approach	[97]
NiO	<i>Hordeum vulgare</i> plant	degradation of methylene blue dye	bioremediation of industrial and domestic waste	[98]
NiO	<i>Sageretia thea</i>	antileishmanial and moderate antioxidant potential	Bioreduction, green approach	[99]
NiO	Eucalyptus globulus plants	Inhibition of growth and biofilm formation of clinical bacterial isolates	ecofriendly approach	[100]
NiO	Coriandrum sativum Leaf	Catalytic activity toward the oxidation of styrene to benzaldehyde.	Inexpensive and ecofriendly	[101]



NiO	Calotropis gigantea	degradation of methylene blue dye	bioremediation of industrial and domestic waste	[100]
NiO	Aspalathus Linearis	Electrochemical activity	ecofriendly approach	[102]
NiO	Moringa oleifera extract	Antimicrobial against infectious diseases	Bioreduction, green approach	[103]
NiO	<i>Agathosma betulina</i>	effective chelating agent	ecofriendly approach	[104]
NiO	Ocimum sanctum	removal of dyes and pollutants	bioremediation of industrial and domestic waste	[105]
NiO	<i>Nephelium lappaceum</i> L., peel	antibacterial activity	Bioreduction, green approach	[106]
NiO	Aegle marmelos leaf	photocatalyst for the degradation and cytotoxic activity	bioremediation of waste	[107]
NiO	Syzygium cumini	antioxidant and dyes removal activity	bioremediation of industrial and domestic waste	[108]

These microbes have the ability to decrease metal ions and produce stable, well-shaped nanoparticles. The production of NiO nanoparticles using *Aspergillus niger*, which produced excellent catalytic activity, is a prime example [104]. Rice husk and sugarcane bagasse are examples of agricultural wastes that are becoming more and more significant. These waste materials serve as reducing agents and resources, effectively producing CuO and NiO nanoparticles while resolving waste disposal issues.

5.1 Comparative Effectiveness

Plant-based FeO nanoparticles, such as those derived from hibiscus and neem, have demonstrated remarkable activity in Fenton-like reactions and in the degradation of contaminants. Because it is relatively easy to extract bioactive compounds from plants, the procedure is simple to implement and scale up. This synthesis method's environmental friendliness is further enhanced by avoiding hazardous ingredients. Fruit waste, such as banana and orange peels, can be used to create CuO nanoparticles, which show a strong photocatalytic ability to break down organic pollutants. These fruit-derived techniques give value to otherwise wasted material while lowering costs. The benefits of this strategy are shown by CuO's efficacy in redox reactions. In environmental applications, such as the reduction of CO₂, NiO nanoparticles produced by fungal processes or from agricultural waste have demonstrated encouraging outcomes. *Aspergillus niger* and other fungi aid in the development of stable structures and particular forms [109]. The procedure is

both feasible and sustainable when biowaste like sugarcane bagasse, is used.

5.2 Sustainability Considerations

Green synthesis techniques have several environmental benefits over conventional chemical synthesis. Traditional methods frequently use hazardous chemicals and solvents that endanger human health and the environment. On the other hand, green synthesis lessens the ecological footprint by using natural, safe and biodegradable components. Many green pathways can be used at standard temperatures and pressures, which lowers the energy needed compared to energy-demanding processes like hydrothermal or vapor-based approaches. Additionally, utilizing agricultural waste gives it value and promotes the idea of a circular economy. When it comes to CuO and NiO nanoparticles made from food industry waste, this is particularly important [110].

5.3 Catalytic Performance Comparison

The synthesis process and the impact of the biological components employed determine the green-synthesised nanoparticles' catalytic potential. High surface area and functional groups in FeO nanoparticles derived from plant extracts can improve pollutant degradation, particularly in Fenton-like systems. CuO nanoparticles exhibit high redox and photocatalytic activity efficiency. The inclusion of natural chemicals improves stability and reactivity toward target pollutants when made with fruit peels.



NiO nanoparticles made from waste materials and fungi exhibit good performance in oxidation-reduction and CO₂ reduction processes. Their enhanced functionality is a result of the structural characteristics that fungal synthesis imparts.

The comparative analysis of green-synthesised FeO, CuO and NiO nanoparticles shows promise for high-performance and long-lasting catalytic applications. In addition to producing active and adaptable nanomaterials, plant materials, microorganisms, and agricultural byproducts offer a safer substitute for chemical synthesis [28]. More research is required to investigate new biological resources and enhance the scalability and reproducibility of these ecofriendly techniques. Green-synthesized nanoparticles will be essential in advancing ecofriendly chemical processes and solutions as businesses progressively embrace greener technology.

6. Catalysis Applications of Green-Synthesized Nanoparticles

6.1 Catalysis Overview

In many industrial and environmental processes, catalysis is essential because it lowers the activation energy of chemical reactions, accelerating them. It is crucial for industries including pharmaceuticals, energy production, environmental control and chemical manufacturing. Because of their huge surface area, high reactivity and modifiable physical and chemical properties, nanomaterials are very effective as catalysts. Among these, green-produced FeO, CuO and NiO nanoparticles are particularly attractive substitutes for traditionally manufactured catalysts, providing an ecofriendly path with effective catalytic activity.

Catalysts are employed in modern industry to facilitate important reactions that produce chemicals, fuels and medications. They are also essential for energy-related technologies and for cleaning up contaminated air and water. The surface area and quantity of reaction-ready active sites of a catalyst are frequently critical factors in its performance. Nanoparticles offer many active spots due to their very small size. Nanoparticles made using green synthesis are safe and work well. They use natural polymers, microorganisms or plant extracts. They are renewable and non-toxic. This means they pose fewer threats to human health and the environment. These particles provide a more sustainable catalytic solution. They

break down pollutants, make useful compounds and produce clean energy.

FeO, CuO and NiO nanoparticles made by eco-friendly methods show excellent water cleaning abilities. They help remove dangerous materials like dyes and heavy metals. They do this through adsorption, photocatalysis, and redox processes. Also, NiO and CuO nanoparticles help electrochemical reactions. They increase overall energy efficiency in clean energy technologies. Examples include batteries, fuel cells and capacitors. Catalysis plays an important role in environment repair. This is especially true for treating industrial and farm waste. FeO, CuO and NiO nanoparticles help break down dangerous substances. These include chemicals, dyes, and insecticides. They do this by causing oxidation. Catalysts help vital energy-related processes. These include carbon dioxide (CO₂) conversion and hydrogen creation. Green-synthesized NiO nanoparticles are useful in sustainable energy systems. They show good results in redox processes and CO₂ reduction. In the chemical industry, nanoparticles often speed up reactions. This happens during the making of complex molecules like farm chemicals and medicines. Their high reactivity leads to better yields and faster production.

Nanoparticles give more contact surfaces for chemical reactions. This is due to their small size. This improves the outcome. The green production method further improves the structure and effectiveness of these catalysts. The final products are often safe for living things. They also have no harmful residues. This is because they are made using natural polymers, microorganisms, and plant materials. Because of this, they are very helpful where safety is crucial. Examples include pollution control and medicine. Using renewable materials also helps sustainability. It reduces the use of toxic chemicals throughout the making process.

Energy systems, environment control and chemical manufacture often use redox processes. These involve the exchange of electrons. Nanoparticles are perfect for these reactions. They are efficient electron donors and acceptors. FeO nanoparticles help make hydroxyl radicals in Fenton-like reactions. These radicals break down organic waste in water. This makes the method good for wastewater treatment. Particles like CuO and NiO absorb light during photocatalysis. This creates reactive species. These can either remove pollutants or cause helpful chemical changes. Renewable energy and environment technologies especially depend on these processes.

Green synthesis of these catalytic nanoparticles avoids dangerous processes. It also makes very effective catalysts. These are good for widespread industrial use. The functions of FeO, CuO and NiO nanoparticles will be discussed in detail in the next sections. The focus will be on their uses in chemical synthesis, renewable energy and pollution treatment.

6.2 FeO in Catalysis

The catalytic features of iron oxide nanoparticles, such as FeO, FeO₃ and FeO₄, are being researched much. They are good for many processes. This is especially true for cleaning up pollutants. This is due to their magnetic behaviour, large surface area and good chemical stability. FeO nanoparticles made in a green way show excellent effectiveness. They break down organic contaminants and clean wastewater. Fenton-like reactions are a main catalytic use for FeO. These reactions make reactive molecules to clear water of impurities. This section covers the benefits of FeO nanoparticles in eco-friendly chemical processes. It also talks about how they help these types of reactions.

6.2.1 Fenton-Like Reactions for Pollutant Degradation

Strong oxidizers called hydroxyl radicals ($\cdot\text{OH}$) form when iron-based nanoparticles combine with hydrogen peroxide (H₂O₂). This happens in Fenton-like reactions. These radicals change dangerous materials into less dangerous, simpler forms. Examples include industrial chemicals, pigments, and medicine residues. They become things like carbon dioxide and water. FeO nanoparticles greatly increase how well this process works. This is due to their high reactivity and surface area.

This makes them perfect for water purification. These processes can happen in both neutral and acidic environments. So, they can be used in many different wastewater treatment systems. Green-synthesized FeO nanoparticles have been used effectively. They remove common textile industry contaminants. Examples include congo red, rhodamine B and methylene blue. For example, FeO₄ nanoparticles from neem leaf extract show almost complete removal of methylene blue colour [111]. This happens under mild reaction conditions. By avoiding the use of harsh chemicals, this ecofriendly process is safer and less harmful to the environment.

A schematic of the photocatalytic degradation of methylene blue is presented in Figure 6. Likewise, FeO₃ nanoparticles made from green tea extract have been used to remove pharmaceutical contaminants in water such as hormone-disrupting substances and antibiotics. These illustrations show how iron oxide nanoparticles that have been greenly manufactured can be effective instruments for environmental preservation by fusing sustainability with efficiency.

These pollutants, which are difficult to break down by conventional wastewater treatment processes, are effectively degraded by hydroxyl radicals generated through the catalytic activity of FeO nanoparticles. This makes green-synthesized FeO nanoparticles a promising solution for addressing pharmaceutical pollution in aquatic environments.

6.2.2. Heterogeneous Catalysis in Environmental Remediation

Apart from Fenton-like reactions, FeO nanoparticles also function as heterogeneous catalysts in various environmental remediation processes. Heterogeneous catalysis refers to reactions where the catalyst is in a different phase (solid) than the reactants (liquid or gas), allowing for easier separation and reuse of the catalyst. FeO nanoparticles, with their magnetic properties, are especially suited for this role because they can be easily recovered from the reaction mixture using an external magnetic field, reducing waste and operational costs.

FeO nanoparticles are widely used in the adsorption and reduction of heavy metals, such as arsenic, chromium, and lead, from contaminated water. The large surface area of Fe₃O₄ nanoparticles enables them to adsorb metal ions effectively, while their catalytic activity facilitates the reduction of these ions into less toxic or removable forms. For example, Fe₂O₃ nanoparticles synthesized using orange peel extract have been shown to adsorb and reduce hexavalent chromium (Cr(VI)) to the less toxic trivalent chromium (Cr(III)), offering a sustainable solution for heavy metal contamination.

Persistent organic pollutants, such as polychlorinated biphenyls (PCBs) and pesticides, are difficult to break down and pose a serious threat to the environment and human health [112].

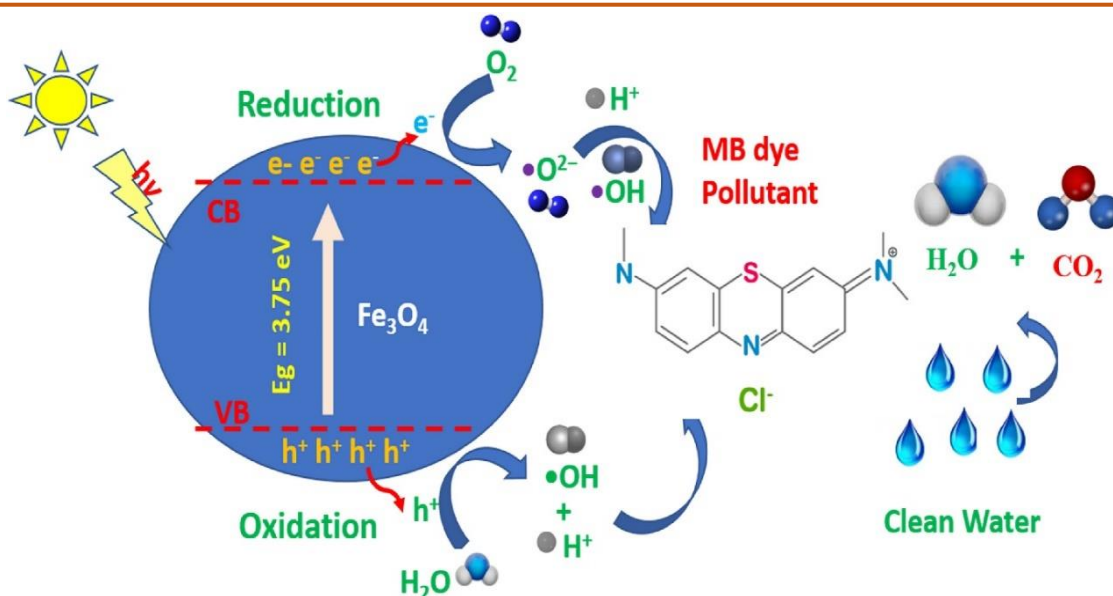


Figure 6. Schematic depicting photocatalytic degradation of MB dye [111]

Green-synthesized FeO nanoparticles have shown great potential in catalyzing the degradation of POPs through advanced oxidation processes. In one study, Fe₃O₄ nanoparticles synthesized using hibiscus flower extract were used to degrade chlorinated pesticides in soil, achieving significant pollutant removal through catalytic oxidation. The magnetic characteristics of FeO nanoparticles, which make separation and reuse simple, are one of its main advantages. FeO nanoparticles are easily extracted from the solution with a simple magnet after a catalytic reaction is finished. They are very efficient and cheap for continuous use in industrial settings. This includes wastewater treatment plants. This is due to their ability to separate using magnets. Because they can be used again, catalyst loss greatly reduces. This is important for cutting down on operating costs.

6.2.3. Photocatalytic Applications of FeO Nanoparticles

Iron oxide (FeO) nanoparticles can absorb light energy. This is especially true from UV or visible sources. This ability to drive chemical processes has drawn much attention in photocatalysis. Using light as a clean energy input is a generally accepted eco-friendly way to reduce pollution. FeO nanoparticles show good results in many photocatalytic uses. These include hydrogen production, organic pollutant breakdown and water splitting. In one notable study, FeO₃ nanoparticles made from *Moringa oleifera* extract helped break down man-made colors. This happened when exposed to visible light [68]. These green-synthesized nanoparticles effectively broke down

Rhodamine B and methyl orange in water. FeO₃'s ability to create electron-hole pairs when exposed to light is the main reason for its photocatalytic activity. The reactive oxygen species made by these charge carriers with water molecules break down the dye molecules. FeO nanoparticles help make hydrogen through water splitting. This is in addition to removing pollutants. In this light-driven process, FeO₄ nanoparticles, in particular, work as catalysts. They help turn water into hydrogen gas [69]. Green synthesis makes particles with large surface areas and better light absorption. This increases their efficiency and catalytic behaviour. These features make them appealing for renewable energy solutions. This is where sustainability and low cost are crucial.

6.2.4. Advantages of FeO Nanoparticles in Catalysis

Green synthesis of FeO nanoparticles has several advantages over traditional chemical methods. This is especially true for catalytic uses. Plant extracts and other natural resources are used in green approaches. They do not use harmful chemicals like standard synthesis ways. This makes the process safer for human health and the environment. This is very important for pollution control and water purification. There, it is vital to stop dangerous byproducts from entering. Another big benefit is the cost savings. This comes from using cheap, easy-to-get raw materials. Examples include farm waste and herbal extracts. These techniques often work best in mild conditions. This means room temperature and normal pressure. This cuts production costs and helps save energy.



Green-synthesized FeO nanoparticles can therefore be used widely in large-scale catalytic applications. These include removing industrial pollutants and wastewater treatment [81]. These nanoparticles show strong catalytic potential in many uses. Examples include light-driven processes, heterogeneous catalysis and Fenton-like reactions. Their efficiency in removing organic contaminants, absorbing heavy metals and encouraging hydrogen production increases their importance in environment clean-up and renewable energy. Green-synthesized FeO nanoparticles reduce financial and environmental costs. They not only improve how these technologies work but also support sustainability goals. Future research should aim to improve their features and increase their usefulness in industry.

6.3 CuO in Catalysis

Copper oxide nanoparticles (CuO NPs) show promise as catalysts. This is due to their unique electrical structure, large surface area, and remarkable catalytic activity. CuO can successfully take part in many chemical processes. This is especially true for oxidation-reduction reactions and the breakdown of organic contaminants. Their growing use in energy-related and environment repair technologies shows how useful they are. This section looks at the catalytic functions of CuO nanoparticles made with green synthesis techniques. It focuses on how they react with oxidation-reduction and their possible uses in wastewater treatment.

6.3.1 Oxidation-Reduction Reactions

CuO nanoparticles are well known for their role in redox reactions. These are essential to energy systems, environment uses, and chemical making. These nanoparticles can effectively drive many chemical changes. They work as both electron donors and acceptors. This is because copper's redox activity allows it to switch between Cu^{2+} and Cu^+ states [113]. Their strong catalytic activity mainly comes from their ability to help electron movement. A well-known example is the breakdown of hydrogen peroxide (H_2O_2) into water and oxygen. This reaction is commonly used in environmental work to clean up contaminants. CuO nanoparticles make this process work much better. They do this by stabilizing intermediates. This helps H_2O_2 break down more efficiently. This raises the overall effectiveness of removing pollutants from water.

6.3.2 Degradation of Organic Pollutants in Water

Removing organic pollutants from wastewater is a main use for CuO nanoparticles. These include numerous industrial chemicals, medications, and colours that are frequently challenging to remove with traditional techniques. Green-synthesized CuO nanoparticles have demonstrated outstanding performance in photocatalytic dye degradation, particularly those made with plant-based extracts. When exposed to light, these nanoparticles produce very reactive species like hydroxyl radicals ($\bullet\text{OH}$), which degrade dye molecules like rhodamine B and methylene blue into less toxic forms [43]. For example, CuO nanoparticles made from extract from banana peels have shown good methylene blue degradation when subjected to UV light. This demonstrates how they could be used in real-world wastewater treatment systems. They play a part that goes beyond dyes. Pharmaceutical residues that linger in water bodies and are resistant to conventional treatment, such as tetracycline and diclofenac, can also be effectively broken down by CuO nanoparticles. Together with H_2O_2 , the presence of Cu^{2+} in the reaction system aids in the generation of reactive oxygen species, which target and break down these medicinal substances. An increasing issue over new pollutants in water supplies is addressed by this feature.

6.3.3 Benefits of CuO Nanoparticles in Catalytic Applications

There are various benefits of creating CuO nanoparticles using ecofriendly techniques. In order to minimize the use of hazardous chemicals and solvents, these techniques usually rely on natural reducing agents, such as plant extracts. The synthesis method is therefore safer and more environmentally beneficial. Additionally, the process uses agricultural byproducts to reduce production costs, which makes the technology economically feasible for large-scale uses like treating municipal wastewater.

Green-synthesized CuO nanoparticles' large surface area and porous shape provide improved catalytic activity. These traits increase their interaction with reactants, which accelerates reaction rates and increases efficiency. In other applications, these nanoparticles are combined with magnetic materials to facilitate magnetic separation, which makes recovery from reaction mixtures simple [94]. Their ongoing usage in industrial operations is supported by their reusability, which eventually lowers long-term expenses.



There are numerous applications for CuO nanoparticles. They assist in the removal of hazardous dyes and medication residues from wastewater. The water is improved as a result. Their catalytic properties also aid in the functioning of energy systems. These include CO₂ conversion and hydrogen production. These are key for sustainable energy solutions. Furthermore, CuO acts as a strong catalyst in oxidation and coupling reactions during organic synthesis. This often leads to higher yields and quicker process times. In general, CuO nanoparticles made in a green way offer an effective and sustainable catalysis technology. This is especially true for oxidation-reduction and water purification processes. Their excellent performance and small environmental impact make them useful tools. These tools are for synthetic chemistry, pollutant removal and renewable energy creation. Ongoing research continues to expand their uses. This opens new paths for cheap and eco-friendly technical solutions.

6.4 NiO in Catalysis

Nickel oxide (NiO) nanoparticles have drawn much attention. This is because of their many catalytic uses. These are especially notable in oxidation-reduction reactions and environmental clean-up. Their ability to switch between Ni²⁺ and Ni³⁺ oxidation states is a major factor. This helps foster different chemical reactions. Because of these features, NiO is a valuable catalyst. It finds use in a number of energy-related technologies. It also helps processes like carbon dioxide (CO₂) conversion and pollutant breakdown. This section highlights the catalytic importance of NiO. It gives special attention to its role in environmental clean-up, CO₂ reduction, and redox reactions.

6.4.1 Role of NiO in Redox Reactions

NiO nanoparticles work well in redox systems. These involve both oxidation and reduction reactions. Their ability to switch between several oxidation states helps electron movement. It also makes the overall reaction more efficient. NiO is good for processes like alcohol oxidation, hydrogenation, and CO₂ conversion. This is due to its redox flexibility. Specifically, green-synthesized NiO particles show good results. They help oxidize alcohols to ketones and aldehydes [114]. For example, NiO nanoparticles that help oxidize primary and secondary alcohols under mild conditions have been made. These use *Moringa oleifera* leaf extract. This method keeps catalytic activity. It also avoids

harmful oxidizers and makes environmental safety better.

6.4.2 CO₂ Reduction Catalysis

Converting CO₂ into useful goods is a main scientific goal. This is important for fighting climate change. In this area, NiO nanoparticles offer good chances. They help make substances like methanol, methane, and other hydrocarbons. They do this by electrochemically reducing CO₂. Temperature, how much electron donor is available, and catalyst structure are some things that affect catalytic activity. Green-synthesized NiO shows strong activity and selectivity for CO₂ conversion. This is especially true for NiO made from farm waste like sugarcane bagasse. It makes valuable compounds like formate and methanol. Such renewable resources are used to encourage sustainable progress in energy technology. They also cut down on production costs.

6.4.3 Environmental Remediation Processes

NiO nanoparticles show great promise in treating environmental contaminants. This is especially true in soil cleaning and water purification. Their photocatalytic activity helps break down toxic organic materials. This happens when they are exposed to UV or visible light. NiO creates reactive species during this process. These break down harmful substances like colors and insecticides [101]. For example, NiO produced with extract from *Coriandrum sativum* (coriander) has demonstrated effectiveness in breaking down dye contaminants in water systems [115]. In addition to photocatalysis, NiO contributes to the removal of heavy metals like chromium and lead. Its redox nature helps transform hazardous metal ions into harmless ones, and its large surface area facilitates effective adsorption. NiO is a viable option for water treatment technologies because of its dual action.

6.4.4 Advantages of NiO Nanoparticles in Catalysis

Green synthesis methods improve the applicability of NiO in catalysis in a number of ways. The production process is more ecofriendly when methods based on plant extracts, fungus, or agricultural leftovers are used instead of dangerous chemicals. Additionally, it guarantees that the produced nanoparticles are appropriate for delicate uses. The cost of making NiO nanoparticles is kept cheap because renewable resources, such as agro-



waste, are readily accessible. Furthermore, high surface area, regulated particle shape and superior purity are all desired characteristics of green-synthesized NiO that enhance catalytic efficiency.

One major benefit of NiO nanoparticles is their magnetic characteristic, which makes recovery and reuse after reactions simple. Their large-scale industrial application is supported by this feature, which also helps to lower operating costs [112]. In addition, NiO nanoparticles have shown promise in a variety of applications. They effectively remove both organic and inorganic pollutants from wastewater. They also help energy systems by aiding CO₂ conversion and hydrogen production. This supports cleaner energy sources. In addition, their use in chemical synthesis improves overall reaction results and selectivity. NiO nanoparticles are a promising tool in many industries. This is due to their special catalytic qualities and eco-friendly creation. Their help in making sustainable technologies will likely grow as research continues. This opens the door for more effective and clean industrial processes.

7. Conclusion

This study looked at advances in eco-friendly ways to make magnetic nanoparticles. It focused on iron oxide (FeO), copper oxide (CuO) and nickel oxide (NiO) nanoparticles. The study highlights how vital it is to make these minerals using environmentally sound methods. It also highlights how important plant extracts, microbes and agricultural waste are as reducing agents. Green synthesis techniques offer a number of benefits, such as lower energy usage, the removal of hazardous byproducts and improved biocompatibility for a range of catalytic uses. Green-synthesized FeO, CuO and NiO nanoparticles have proven to be excellent catalysts in oxidation-reduction processes, CO₂ reduction and pollutant degradation. The catalytic activities of these nanoparticles provide sustainable solutions for critical challenges in environmental remediation and energy production in wide-range of industrial applications.

8. Future Research Directions

As the field of green nanotechnology continues to evolve, several avenues for future research can be pursued to further enhance the synthesis and application of magnetic nanoparticles. Future research should focus on exploring new biological sources for nanoparticle synthesis, such as lesser-known plants,

algae, and microorganisms. Investigating the mechanisms behind nanoparticle formation in these biological systems can lead to the discovery of novel reducing and stabilizing agents for the improvement of efficiency and scalability of synthesis processes. The parameters like temperature, pH, and reaction time can be fine-tuned by green synthesis methods to control over nanoparticle size, shape and distribution. The systematic studies to identify the optimal conditions for synthesizing high-performance nanoparticles will enhance their effectiveness in various applications. Investigating the surface modifications and functionalization of green-synthesized nanoparticles can improve their catalytic performance. Research should explore techniques for doping or combining nanoparticles with other materials to create hybrid catalysts that exhibit superior reactivity and selectivity in targeted reactions.

Beyond environmental remediation and energy production, the potential applications of green-synthesized nanoparticles can be expanded into fields of biomedicine, sensors and advanced materials. The interaction analysis of these nanoparticles with biological systems can lead to new therapeutic strategies and drug delivery systems, while their unique properties can be harnessed in the development of high-performance sensors and devices. The comprehensive lifecycle assessments (LCAs) of green-synthesized nanoparticles can help quantify their environmental benefits and identify any potential sustainability concerns associated with their production and use. This information will be critical for guiding the responsible development and commercialization of these materials in various industries.

Translation of laboratory green synthesis methods into practical applications will be essential for realizing the full potential of these nanoparticles. Joint research efforts can facilitate the optimization of synthesis processes for industrial scalability and innovative solutions to address specific environmental and energy-related challenges. In conclusion, the advancements in green synthesis methods for FeO, CuO, and NiO nanoparticles provide the sustainable catalysts for significant environmental and industrial applications. As research in this field progresses, it has the potential for cleaner technologies, enhanced environmental remediation and the sustainable energy production for sustainable future.



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Conflict of interest

The Authors declares that there is no conflict of interest anywhere.

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Yes

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