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Promising Green Method for Preparing Nano-Particles and their Famous Applications: A Review

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Abstract

Nanoparticles are promising materials for a wide range of uses, including energy storage and cleaning up the environment, since they have amazing redox properties, are chemically stable, and have a huge surface area. Traditional synthesis methods, on the other hand, have difficulties with safety and the environment because they often employ harmful chemicals and need a lot of energy. As a result, green synthesis has become one of these alternatives. It uses biological resources like microbes, plant extracts, and biopolymers. This paper goes into detail on the most recent developments in the ecologically friendly synthesis of Co_3O_4 nanoparticles, including essential approaches as those that use plants, microbes, and biopolymers. We employ particle size, shape, surface area, response time, yield, and functional performance to compare and contrast different techniques. The article goes on to discuss about how Co_3O_4 is used in photocatalysis, wastewater treatment, supercapacitors, and battery systems. It also talks about common ways to characterize it, such as XRD, SEM, FTIR, UV-Vis, and BET. We also look at some of the challenges that are happening right now, such as not being able to scale up, not having enough lifecycle evaluations, and not having clear procedures. The last part of the report talks about some ways that the authors think could lead to big improvements in hybrid materials, large-scale manufacturing, and sustainability indicators. The main purpose of this assessment is to support the growth of green nanotechnology and encourage its use in practical solutions for energy and the environment.

Keywords: Green synthesis; Nanotechnology; Plant-mediated synthesis; Eco-friendly nanotechnology

1. Introduction

Nanotechnology has opened up a new field of study that lets scientists make high-tech materials with unique physicochemical properties. Nanoparticles of cobalt oxide (Co_3O_4) have been the focus of a lot of research in the field of nanomaterials because they have great electrochemical performance, chemical stability, and catalytic activity. Cobalt oxide is great for a lot of energy and environmental uses since it has so many good properties. These include supercapacitors, lithium-ion batteries, photocatalysis, and cleaning up wastewater. Sol-gel, hydrothermal, and precipitation techniques are some of the physical and chemical methods that have been employed to make Co_3O_4 nanoparticles for a long time. On the other hand, traditional methods are very bad for people's and the environment's health since they use a lot of energy, hazardous chemicals, and generate deadly by-products. Recently, green synthesis methods have become more popular as a way to solve these problems. These methods use natural sources like microorganisms, plant extracts, or biodegradable polymers to reduce and stabilize molecules in a way that is good for the environment. Green synthesis has many benefits outside lowering the cost of production. These include milder reaction conditions, better biocompatibility, and a smaller impact on the environment. There has been a lot of recent research into different techniques to make Co_3O_4 nanoparticles that are good for the environment, but the results have been all over the place when it comes to particle size, shape, surface area, and functional performance. Even while there is more and more writing on the issue, there aren't many critical reviews of these new ideas, especially when it comes

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to how they affect the environment and energy use. This review tries to fill that gap by carefully looking at the most recent developments in making Co_3O_4 nanoparticles in a way that is good for the environment. We look at the different ways to make things, assess their pros and cons, and talk about how they work in crucial application areas. The evaluation goes on to say where there isn't enough research and what needs to be done in the future to make cobalt oxide nanoparticles that last.

2. Scope of the Review

This review article talks about the most recent advances in making cobalt oxide (Co_3O_4) nanoparticles that are good for the environment and how they might be used in the energy and environmental sectors. We won't employ traditional physical and chemical fabrication methods that use toxic chemicals or a lot of energy. Instead, we will only look at synthesis methods that are good for the environment and can be used again and again. The review's main focus is on research that was published between 2013 and 2025 and focuses on: Making nanoparticles with naturally occurring stabilizing and reducing agents, like microbes, plant extracts, and biopolymers. The nanoparticles' physical and chemical properties, such as their size, shape, and surface area. A look at the ways that Co_3O_4 made in ways that are good for the environment were described. These nanoparticles are useful in the environment because they can clean up wastewater, break down contaminants, and do photocatalysis. Energy systems, such as lithium-ion batteries, supercapacitors, and electrocatalytic processes. The study looks at and analyzes a number of green synthesis processes, including their pros and cons. It also talks about research gaps that need to be filled and possible future opportunities. Studies published in journals, patents, and conference proceedings will be looked at as long as they follow the rules of green chemistry. This scope not only gives us a better understanding of the real-world impact of sustainable nanotechnology operations that use Co_3O_4 to solve global energy and environmental problems, but it also ensures that these techniques are thoroughly and focused on.

3. Literature review

Nanomaterials made from Co_3O_4 are very important. Nanomaterials are very important because they have better properties than bulk materials. Cobalt oxide (Co_3O_4) nanoparticles are very interesting because they are very stable at high temperatures, have magnetic properties, and can function as catalysts. This makes them useful for a wide range of things, such as storing energy, cleaning up the environment, and speeding up chemical reactions. Nanomaterials have become an important aspect of modern science and technology because their properties are so distinct from those of bulk materials. At the nanoscale, materials act very differently because of quantum phenomena and a very high surface-to-volume ratio. These changes give nanoparticles new optical, chemical, electrical, and mechanical capabilities that make them better than more typical materials. The fact that nanomaterials have a much larger surface area is one of their most important features. As the size of the particles gets smaller, the surface-to-atomic-number ratio grows at an exponential rate. Because they have a large surface area, they are exceedingly reactive and can interact with other compounds. This makes them great for catalytic processes, sensors, and drug delivery systems. This feature is very important for cleaning up the environment since it lets materials interact with pollutants in the best way possible. Nanoparticles can be controlled in a lot of ways. Scientists can change the properties of the chemicals they make by controlling their size, shape, and crystal structure during synthesis. The amazing ability of today's materials to adapt makes a lot of things conceivable. For example, targeted medication delivery in cancer therapy, high-efficiency solar cells, and ultra-sensitive biosensors are all possible. They may operate in a lot of different professions and industries because they are very flexible. They can be used in medicine for things like tissue engineering, targeted drug delivery, and diagnostics. They help make electronic parts that are smaller, quicker, and work better. Nanomaterials are very important in the energy business because they help fuel cells, batteries, and supercapacitors work better. Some of its functions in environmental science are cleaning water, filtering air, and breaking down pollutants. Nanoparticles are a game-changer in current and future technology because they can be used in so many ways. Nanomaterials have become an important aspect of modern science and technology because their properties are so distinct from those of bulk materials. At the nanoscale, materials behave very differently because of quantum phenomena and a very high surface-to-volume ratio. These changes give nanoparticles new optical, chemical, electrical, and mechanical capabilities that make them better than more typical materials (Zhang et al., 2021). The fact that nanomaterials have a much larger surface area is one of their most important features. As the size of the particles gets smaller, the surface-to-atomic-number ratio grows at an exponential rate. Their large surface area makes them exceedingly reactive and able to interact with other chemicals, which makes them great for catalytic processes, sensors, and drug delivery systems. This feature is useful for environmental applications that need to remediate materials and pollutants by getting them to touch as much as possible (Sahu & Tiwari, 2024). Nanoparticles are very easy to manage. Scientists have full control over the chemical makeup, size, shape, and crystal structure of the materials they make, which lets them change their attributes. Materials can be changed to do specific jobs better since they can be changed. For example, they can be used in cancer treatment, high-efficiency solar cells, or ultra-sensitive biosensors (Zhang et al., 2021). They can work in a lot of different professions and industries because they are so flexible. They can be used in medicine for things like tissue engineering, targeted drug delivery, and diagnostics. They help make electronic parts that are smaller, quicker, and work better. Nanomaterials are very important in the energy business because they make fuel cells, batteries, and supercapacitors work better. They are used in environmental science to break down pollutants, clean the air, and make water safe to drink (Sahu & Tiwari, 2024). Nanoparticles are a game-changer in current and future technological breakthroughs since they may be used in so many different ways.

4. Significance of Co_3O_4 Nanomaterials

Cobalt oxide nanoparticles are different from other transition metal oxides because they have unique physicochemical properties and are used a lot. Their importance begins with how well they work as catalysts. Co_3O_4 is a strong redox catalyst because it shows both the reduced and oxidized forms of Co^{3+}. The oxygen evolution reaction (OER) is an important part of electrochemical water splitting that makes clean hydrogen fuel. Its dual valence structure lets it take part in many oxidation-reduction reactions, like the catalytic oxidation of organic pollutants (ACS Omega, 2022; Dang, 2025). Co_3O_4 nanoparticles are widely used in supercapacitors and lithium-ion batteries for storing energy. The nanostructured nature of the material gives it a lot of surface area and active sites, which makes it better at storing and moving charge. Nanomaterials are these materials may be able to conduct reversible redox processes and have stable structures. This means they can be employed in battery systems that can hold more power and last longer. Co_3O_4 nanoparticles are also useful for the environment. They can be employed as a long-term way to clean up polluted water and air since they break down organic pollutants when they are exposed to light. Environmental Science applied nanoparticles make reactive oxygen species when they are exposed to light. These materials can break down harmful contaminants into simpler or biodegradable forms. Co_3O_4 also has some very cool magnetic properties. It doesn't have strong ferromagnetic properties, but it does show antiferromagnetic behavior and has a high magnetic susceptibility on the nanoscale. Magnetic nanoparticles can be used to pull out certain molecules or contaminants from difficult mixtures. This makes them useful in biological imaging technologies like MRI and magnetic separation technologies. The last thing to say is that Co_3O_4 nanoparticles are quite stable in both heat and chemicals. They are perfect for a wide range of industrial and environmental uses that need to be reliable for a long time because they can handle intense heat and acid conditions. One reason why they are useful for various scientific and engineering purposes is that they are strong enough to hold up under harsh conditions. Kamalam et al. (2024) reported that the hydrothermal method is a simple and effective way to make highly crystalline nanomaterials, such as cobalt oxide (Co_3O_4) nanoparticles. Photoluminescence (PL), X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), ultraviolet-visible spectroscopy (UV-visible), and other methods of characterization confirmed the nanoparticles' optical and structural properties. The XRD test showed that the Co_3O_4 nanoparticles had an average crystallite size of 64.86 nm and a cubic spinel structure. FTIR measurements showed that there were substantial stretching and bending vibrations between the metal and oxygen, which helped to explain the chemical link. We used UV-Vis. spectra and PL tests to look at the material and find out how well it absorbs light. There was a strong absorption at about 265 nm and a peak in UV emission at 335 nm. Co_3O_4 showed a 60% degradation efficiency in a test that used visible light and photocatalytic degradation to break down methylene blue dye. The results demonstrate that Co_3O_4 nanoparticles could be useful for environmental objectives, notably in treating wastewater, where it is vital to get rid of dyes quickly utilizing visible light. Because of how they are made and how well they work as photocatalysts, Co_3O_4 nanoparticles could be useful in photocatalytic applications in the future. Nanostructured Co_3O_4 provides a lot of advantages over its bulk counterparts when it comes to photocatalytic uses. Cobalt oxide has a lot of surface area at the nanoscale, which means it has more places where dye molecules can stick to it and break down. Recombining electron-hole pairs is another big problem in photocatalysis, but the small size of the particles makes it easier to separate the charges. These properties make Co_3O_4 as a whole better at photocatalytic degradation, which makes it a superior choice for breaking down pollutants [36]. Researchers have looked into ways to improve the photocatalytic properties of Co_3O_4, such as changing the surface, adding more metals, and connecting it with other semiconductors. (Zhang et al., 2021). One of the most important environmental problems right now is the poisoning of water bodies by organic pollutants, especially synthetic colors. Methylene blue (MB), a synthetic dye that is used a lot in the textile, pharmaceutical, and paper sectors, is in wastewater. Methylene blue is still a threat to aquatic ecosystems and people's health because it doesn't break down naturally. It is bad for people as well as aquatic life at high enough levels to irritate their skin and lungs. Because of this, we need effective ways to get methylene blue out of water to safeguard the environment. People are interested in looking into other techniques to get rid of methylene blue, such photocatalysis, because the usual means of treating water don't always work. Cobalt oxide nanoparticles have shown considerable potential in breaking down methylene blue when it is exposed to visible light. When the catalyst absorbs visible light, electrons move from the valence band to the conduction band. This is how Co_3O_4 nanoparticles break down methylene blue by photocatalytic degradation. This process creates reactive oxygen species (ROS), which can break down methylene blue into less harmful byproducts like water and carbon dioxide by joining electrons and holes. The process's efficiency depends on a number of factors, including the size, shape, crystallinity, and surface area of the nanoparticles (Zhang et al., 2021).

5. Challenges with conventional synthesis (toxicity, energy use)

Traditional methods for making cobalt oxide, including hydrothermal or chemical vapor deposition, have problems like possible toxicity, high energy use, and long processing times. These technologies often need complicated processes and toxic chemicals, which could be bad for the environment and people's health. They also cost a lot to make. Nanoscience research is making it more and more important to make NPs in ways that are good for the environment and don't hurt animals. This is because it is getting better at using a variety of fields. Nanotechnologists are working on safe, controlled ways to make NPs because they could be used in many different industries, such as medicine, catalysis, manufacturing, and cleaning up the environment. This is because NPs are very small, porous, and have a high surface-to-volume ratio. The use of harmful chemicals in the past made people more worried about the environment. On the other hand, the use of phytochemicals from plants in green synthesis is becoming more important, in keeping with the United Nations' goals for sustainable development. This is because the NP market is predicted to grow by 2026. Many different kinds of businesses employ metal oxide NPs a lot. Some of these are construction, renewable energy, cosmetics, electronics, textiles, pharmaceuticals, and protecting the environment. From 8 to 14 Some common metal oxides, like ZnO, Al_2O_3, TiO_2, NiO, CeO_2, CuO, and MgO, might be detrimental because they can cause cytotoxicity, oxidative stress, DNA damage, and inflammation. For instance, TiO_2 NPs hurt DNA and ZnO NPs are particularly harmful to lung cells in people. Cobalt oxide (Co_3O_4) NPs, on the other hand, are better for the environment and have many useful and cost-effective uses in science and technology. Cobalt oxide is a fantastic material for mass production because it is cheap and easy to get. This makes the product available to a lot of people. It will last in many different places because it is so chemically stable. There are four more types of cobalt oxide besides coO and co3O4 that are more stable: Co_2O_3, Co_2O_4, Co_2O, and Co_3O_4. There are three distinct oxidation states for cobalt: Co2+, Co^{3+}, and Co^{4+} (Fig. 1A). In the spinel structure (AB_2O_4), Co^{2+} fills eight of the tetrahedral (A-sites) and sixteen of the octahedral (B-sites). The spinel-structured Co_3O_4 stays stable below 891 °C, but when heated over this temperature, it turns into CoO. Because it has a large band gap (1.48–2.19 eV), it is good for use in supercapacitors. Cobalt oxide nanoparticles are common, cheap, p-type semiconductors that are antiferromagnetic and resist corrosion and oxidation very well. They can be used in numerous ways, such as to find gas, treat infections and cancer, store energy, divide water, remove dyes, lower CO_2 levels, give drugs, electrocatalysis, lithium-ion batteries, and supercapacitors. Using traditional synthesis methods like hydrothermal, co-precipitation, sol-gel, chemical reduction, spray pyrolysis, chemical vapor deposition (CVD), microemulsion, sonochemical, laser ablation, mechanochemical processes, ionic liquid assisted, reflux, polyol, pulsed laser deposition, template method, and thermal decomposition takes a lot of time, money, and energy. Hydrazine hydrate (NH_2NH_2) and sodium borohydride (NaBH4) are two examples of dangerous reducing agents that are often utilized. Biogenic processes, on the other hand, are speedier, use plant extracts, microorganisms, algae, and waste products, and are better for the environment. Green synthesis makes stable NPs that are biocompatible and have a low band gap energy because quantum confinement phenomena keep them from breaking down. This means that biogenic cobalt oxide NPs are better for the environment and can be utilized for a longer duration. More articles about making cobalt oxide NPs from plants are being published, which is a sign of a wider move toward more environmentally friendly production (Fig. 1B). Researchers have used lemon extract to make cobalt oxide NPs for LPG gas sensors. Researchers also looked into using wasted apple juice to make cobalt oxide nanostructures with changed surfaces that can help oxygen evolve. A number of recent research that looked at making cobalt oxide NPs in an environmentally friendly way using different natural extracts have revealed that they may be able to fight germs, cancer, and free radicals.

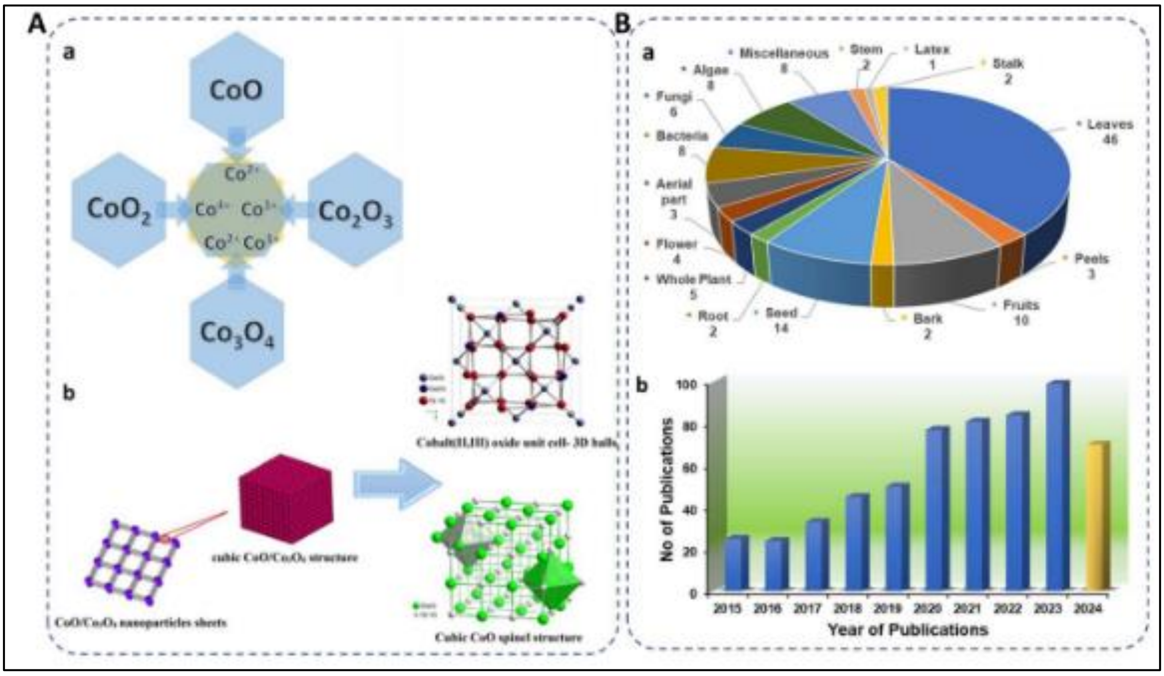

Figure 1 (a) The several kinds of cobalt oxide that are already out there and their oxidation states, and (b) the structure of spinel. 19 (B) (a) Showing biosynthesized cobalt oxide NPs from a variety of biological sources, including gum, sucrose, starch, egg white, cloves, coloring powder, walnut peel, and endemic species. (b) The number of papers published in the last eight years on the "green synthesis of cobalt oxide nanoparticles" (source: Web of Science) as of September 21, 2024

It shows how useful and versatile they are in many areas, including as gas sensing, photocatalytic, and supercapacitor applications. Previous review articles have mostly focused on things like photocatalytic degradation and other subjects, leaving out the biological uses of cobalt oxide NPs made from green materials. For example, Imtiyaz et al. (2024) didn't mention biological uses in their most recent review. Iravani et al. published a review in 2020 that mostly talked about catalytic activity, although they did include biological uses as well. Since then, the field has made significant strides. Mubraiz et al. (2021) also looked into the topic, but they only looked at how well it fights germs, so they didn't cover a lot of ground when it comes to biological uses. This review fills in the blanks by giving a detailed overview of how cobalt oxide nanoparticles manufactured from ecologically benign sources can be used in medicine. This article is different from prior ones since it tries to give researchers who are looking for eco-friendly nanomaterials for medical use useful information that is relevant to the current rise in interest in this area. We look at the newest green synthesis methods that involve bacteria and plant extracts in this study. We focus on the mechanical and environmentally friendly aspects of these new procedures because they are better than traditional ones that could be damaging. We look at the cytotoxic, larvicidal, antileishmanial, hemolytic, anticoagulating, thrombolytic, anticancer, and drug sensing capabilities of cobalt oxide NPs, which have a lot of biological uses. These NPs can be used in many different ways, which shows how flexible and promising they are in medicine. Hikaambo et al. (2021) underline how important it is to make nanomaterials in a way that is good for the environment in their study. To deal with the environmental problems that come with present methods, we describe how to make cobalt oxide NPs utilizing natural resources and living things in a way that is cheap, long-lasting, and safe for living things. This essay looks ahead to what cobalt oxide NPs could be able to do in the future in the field of biomedicine. We think that by pointing out the gaps in our understanding and providing new ways to look into them, we may get scientists to move toward nanotechnology practices that are better for the environment and society (Anuradha et al., 2021).

6. Emergence and need for green synthesis.

The chemical industry is quickly realizing that making cobalt oxide nanoparticles (Co-O NPs) in an environmentally benign and flexible way is a game-changer. Sometimes, traditional methods involve dangerous chemicals and severe conditions, which can cause problems for the environment and cost a lot of money. There are more environmentally friendly choices, like "green synthesis," which uses plants, microbes, or even natural extracts. This method uses stabilizing and reducing agents that are already found in nature, which cuts down on the need of toxic chemicals and energy. The arrival of green synthesis for cobalt oxide nanoparticles has opened up a new era in the production of environmentally friendly and long-lasting nanomaterials. This could change several technical fields. Recently, green synthesis, which is a safe for the environment way to make nanoparticles, has become popular. Iravani and Varma (2020) say that traditional physical and chemical synthesis methods often include dangerous reducing agents, high-energy inputs, and poisonous solvents. These practices have major effects on the health of people and the environment. These methods use a lot of chemicals and energy, which hurts both the environment and the economy. Green synthesis is better since it doesn't utilize harmful chemicals and uses mild reaction conditions, such room temperature and pressure, which saves money and energy. Mubraiz et al. (2021) say that this method is in line with the ideas of green chemistry, which include using renewable biological resources, decreasing waste, and saving energy. Green synthesis is a way to make nanomaterials without using toxic chemicals. It uses reducing and stabilizing agents that come from plants, microorganisms, or natural extracts. Cobalt oxide (CoO) nanoparticles are being used more and more in a wide range of fields, including gas detection, catalysis, energy storage, and biological systems. Because of this, there is a big need for more environmentally friendly techniques to make them. These applications need not only high-performance materials but also production methods that are both environmentally friendly and safe for living things (Imtiyaz et al., 2024). Green-synthesized CoO nanoparticles frequently have better physicochemical features, such as better surface functioning, controlled form, and regulated particle size. These features can improve electrochemical, magnetic, and catalytic performance (Hikaambo et al., 2022). Also, green synthesis gets rid of a lot of the difficulties that come up with regular approaches. For example, nanoparticles manufactured using green chemistry are better for living things and less harmful to cells, making them great for targeted drug administration and biomedical imaging (Anuradha & Raji, 2022). These methods provide you better control over the shape, dispersity, and surface charge of nanoparticles, which makes them better for some uses. Different eco-friendly ways of making CoO nanoparticles have been used to make them. Plant-mediated synthesis is a potential method that uses natural reducing and capping agents present in plants including grapes, citrus fruits, and guava leaves. Iravani and Varma (2020) say that phytochemicals high in antioxidants, like flavonoids and polyphenols, keep cobalt ions nanoparticles stable and stop them from forming. Microorganism-mediated synthesis is another approach that uses cobalt salts that are metabolic byproducts of certain fungus and bacteria. This method is perfect since it is biocompatible and has little effect on the environment. Using eco-friendly technology to manufacture CoO nanoparticles has many benefits. A lot of the time, these processes generate materials with better surface properties and structures. This makes them more useful, safer for biomedical use, and better for the environment. Additionally, green technologies are sometimes better for industrial and large-scale use because they utilize less energy and cost less overall. People are becoming more worried about the environment and sustainability. Making cobalt oxide nanoparticles in a green way is a big step forward in materials science and nanotechnology. We made nanoparticles (NPs) of cobalt oxide by heating cobalt nitrate hexahydrate to low temperatures and using an extract from the peel of the Punica granatum plant. We looked at the characteristics of the cobalt-oxide NPs we made using X-ray powder diffraction, scanning electron microscopy, energy-dispersive X-ray, atomic force microscopy, fourier transform infrared spectroscopy, and UV-visible methods. The cobalt-oxide NPs were all about the same size, between 40 and 80 nm. We tested the photocatalytic activity (PCA) of the NPs we made by lowering the concentration of Remazol Brilliant Orange 3R (RBO 3R) dye to 78.45% (dye conc. 150 mg/L) and exposing 0.5 g of cobalt-oxide NPs to light for 50 minutes. The recent study discovered that P. granatum might be used to make cobalt-oxide NPs for photo-catalytic uses. This is wonderful news because it is both eco-friendly and cheap (Bibi et al., 2017). Cobalt NPs can be used in various ways in everyday life because they are very resistant to rust and corrosion. A lot of different physical and chemical methods have been used to make cobalt NPs, including hydrothermal microemulsion, reduction, high-temperature solution phase, thermal breakdown, and many more. Nanoparticle biosynthesis, on the other hand, has become a major aspect of nanotechnology. This process is better for the environment and costs less than older ones that employ chemicals, high temperatures, and pressure. So, we need to find ways to make and use synthetic materials that are safe for the environment, work effectively, and don't cost too much. People who entered this challenge used a range of biosynthetic methods to make NPs. Using plant-based materials to make NPs is a good alternative to physical and chemical methods. Using plant extract lets you skip the long and complicated steps of physico-chemical techniques. Some of the bioactive parts of plant extracts are tanning agents, flavonoids, saponins, and phenolic acids. These bioactive compounds can not only chelate, but they can also quench singlet oxygen and give hydrogen. Nanoparticles generated by plants are better than those made by physicochemical processes because they can change their oxidation state. Plant extracts don't seem to be poisonous, and they're also easy to deal with and process (Bibi et al., 2017). To create cobalt oxide NPs, 90 mL of freshly extracted peel was combined with a 1 M solution of cobalt nitrate hexahydrate. The mixture was heated to 70 C until it formed precipitates. Then it was cooled to 60 C and kept there for 90 minutes. It was centrifuged for 10 minutes at 14,000 rpm after sitting at room temperature for one night. We used ultrapure water and 100% ethanol to wash the precipitates three times to get rid of any particles or impurities that hadn't reacted yet. Bimbi et al. (2017) say that the collected precipitates were dried in an oven at 60 C for 8 to 9 hours, crushed up, and then looked at. Reaction with thermogravimetry. The study looked at how RBO3R breaks down when exposed to sun radiation and used cobalt oxide NPs that were made. The color faded a lot after 20 minutes of irradiation at a starting concentration of 150 mg/L dye and 0.5 mg of cobalt oxide NPs. By the end of the 50-minute process, the decolorization had reached 78.45%. Figure 2 shows how the dye breaks down, and Figure 8 shows the treated dye's color and UV-vis spectra. Photocatalytic treatment broke down the dye because the dye band got smaller and a new peak appeared as the reaction time got longer. When photo-catalytic degradation happens, the chromophoric group and the dye break down into low molecular weight by-products. The dye breaks down mostly because of the creation of electron and hole (e and h+) on the surface of the catalyst when it is exposed to light. When a water molecule combines with a hole, it turns into an OH radical. On the other hand, the O_2 takes up the e and turns it into OH through HOO and H_2O_2. The OH is a powerful oxidizing agent that breaks down the organic molecule (dye) into H_2O, CO_2, and inorganic ions without being picky. After 50 minutes of radiation exposure, cobalt oxide NPs broke down RBO 3R dye by 78.45%, showing that they work well as dye degraders in sunlight (Bibi et al., 2017).

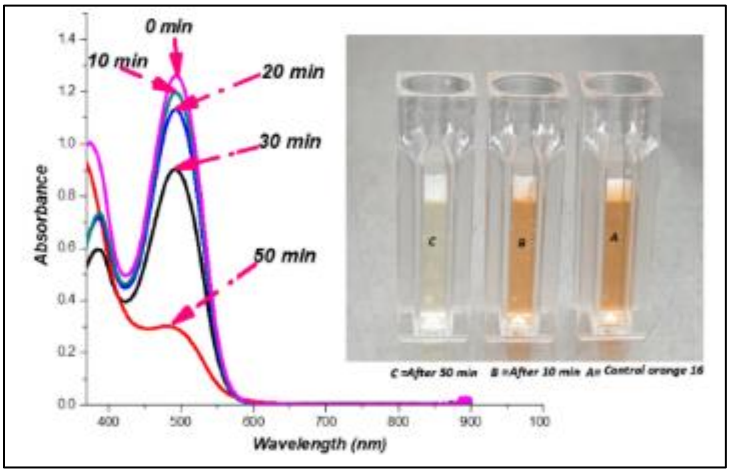

Figure 2 The UV absorption spectra of the dye before and after treatment with cobalt oxide nanoparticles as a catalyst under solar light, and (A–C) pictures of the dye before and after treatment

7. Green Synthesis Techniques

Green manufacturing technologies can make cobalt oxide nanoparticles (CoO-NPs) more effectively and flexibly than standard chemical and physical approaches. Traditional procedures aren't great either because they often require harmful chemicals and a lot of energy. Green synthesis is a safer and more environmentally friendly choice since it uses biological materials like plant extracts, bacteria, or fungus to reduce and stabilize things. The formation of cobalt oxide (Co_3O_4) and other nanoparticles usually involve physical and chemical procedures including sol-gel techniques, hydrothermal synthesis, or thermal breakdown. These technologies can generate nanoparticles with certain shapes; however, they often have a lot of problems. The processes that use a lot of energy, chemicals, and high temperatures, as well as the formation of dangerous byproducts, are some of the most important (Iravani & Varma, 2020). All of these things lead to higher manufacturing costs and more risks to people and the environment. Because nanomaterials are being used more and more in biomedicine, catalysis, and other fields, we need to find more ecologically responsible techniques to make them right now. Research into green synthesis processes has been sparked by a worldwide effort to safeguard ecosystems and natural resources. These solutions are in line with the ideas of green chemistry, which aim to reduce the use of dangerous chemicals, energy use, and waste (Mubraiz et al., 2021). Green synthesis, on the other hand, has shown some promising results. It uses microorganisms, natural biomolecules, and plant extracts as reducing and capping agents to make nanoparticles. Flavonoids, terpenoids, and alkaloids are some of the phytochemicals that these organisms contain. They help keep the nanoparticles stable and lower the amount of metal ions (Iravani & Varma, 2020).

7.1. The Significance of Eco-Friendly Cobalt Oxide Nanoparticle Synthesis

Co-O NPs, or cobalt oxide nanoparticles, are a new type of material that can do a lot of different things. They have potential uses in medical, sensing, energy storage, catalysis, and many other fields. But their physical and chemical qualities rely a lot on how they are made. One of the many benefits of green synthesis of Co-O NPs over more traditional methods is that it has less of a detrimental effect on the environment. Green synthesis works under mild reaction circumstances and doesn't employ dangerous chemicals, which cuts down on energy use and harmful emissions (Imtiyaz et al., 2024). As a result, it has less of an impact on the environment. One of the benefits of green synthesis is that it doesn't cost much. Plant leaves, fruit peels, and microbial cultures are all biological resources that can be used over and over again, are easy to get, and are cheap. They could make the scale synthesis of nanoparticles much better. According to Hikaambo et al. (2022), these materials can be used in a number of ways with little processing, which lowers operational costs even more. Also, green synthesis often makes nanoparticles with special and custom features. When biological molecules and metal ions combine, they make NPs with well-defined shapes, limited size ranges, and functional surface groups. These qualities make Co-O NPs work better in biosensing and catalysis (Anuradha & Raji, 2022). So, green synthesis is a promising alternative to traditional methods that could help us make cobalt oxide nanoparticles with better qualities while also having a less effect on the economy and the environment. This is a very important way to manufacture high-tech materials that are good for the environment and follow the rules. The most advanced way to manufacture nanoparticles uses raw resources in a way that is good for the environment. Green synthesis is also better than physical and chemical synthesis since it takes less time and effort. The physical and chemical properties of cobalt oxide nanoparticles have made them more popular to make in an environmentally friendly way. Using the numerous functional groups found in Psidium guajava leaf extracts, the creation of cobalt oxide nanoparticles is stabilized here. We looked at the biosynthesized cobalt oxide nanoparticles using UV-visible spectroscopy. Also found were phenolic groups, alcohols, carboxylic acids, hydroxyl groups, aromatic amines, and Fourier-transform infrared spectroscopy. There were a lot of peaks between 32.35 and 67.35 ∘ in the X-ray diffraction analysis, and the greatest intensity was at 36.69 ∘ . We discovered that the average size of the particles is 30.9 nm, and the range of sizes is 26 to 40 nm. The EDAX methods show that cobalt is the main element in the environmentally beneficial P. guajava cobalt oxide nanoparticles, making up 42.26 wt% and 18.75 at%. When looked at with a scanning electron microscope, the green P. guajava cobalt oxide nanoparticles seemed like clumps of particles that weren't shaped like anything else. We investigated the antibacterial effectiveness of greenly made P. guajava cobalt oxide nanoparticles against Gram-positive Staphylococcus aureus and Gram-negative Escherichia coli. The inhibitory zone ranged from 7 to 18 mm. We used green-made P. guajava cobalt oxide nanoparticles to test the photocatalytic activity and found that they broke down 79% of the dye. When tested against MCF 7 and HCT 116, P. guajava cobalt oxide nanoparticles demonstrated a much stronger cytotoxic effect than normal cells in the MTT experiment. For MCF-7 cells, the percentage of cell viability of P. guajava cobalt oxide nanoparticles at concentrations of 1.53, 3.06, 6.12, 12.24, 24.48, 50, and 100 μg/mL was 90, 83, 77, 68, 61, 58, and 52%. For HCT 116 cells, it was 82, 70, 63, 51, 43, 40, and 37%. The NPs are results of the production of Co3O4. A solution of cobalt nitrate and 10 milliliters of extract from the leaves of the P. guajava plant were combined together to make cobalt oxide nanoparticles (Co3O4) [67]. We made the cobalt nanoparticles by heating this combination on a hot plate for three hours. After stirring the solution for three hours, it was put in an oven set to 100 °C for five hours to get the dried precipitate. Also, the cobalt oxide NPs that had settled out were heated to 500 °C for three hours to calcine them. Using spectroscopy and microscopy, Goyindasamy et al. (2022) looked at the Co_3O_4 NPs that were made. Characterization We used UV-Vis and FTIR tests to learn more about the characteristics of the P. guajava Co3O4 nanoparticles. Scanning electron microscopy (SEM) with a Zeiss EVO LS10, powder XRD from Therma Corp. in Nicollet, MI, USA, and energy dispersive spectroscopy (EDAX) from Goyindasamy et al. (2022). There are four ways to make green cobalt oxide:

- Making things with microorganisms (bacteria, fungi)
- Making things with biopolymers and other eco-friendly methods • Synthesis that uses plants (phytochemicals as reducing agents)
- A comparison of the size, shape, reaction time, and yield of different eco-friendly methods

Using biopolymers, plant extracts, microorganisms, and other biological sources as reducing and stabilizing agents in nanomaterial manufacturing is better for the environment and more sustainable than using typical chemical synthesis methods. These environmentally friendly methods are getting a lot of attention because they are low in toxicity, save energy, and work well with living things. The three main biological pathways for green synthesis—plant-based synthesis, microbial synthesis, and biopolymer-assisted methods—each have their own distinct mechanisms, benefits, and drawbacks when it comes to nanoparticle features including size, shape, reaction kinetics, and yield. Plant-based synthesis, also known as “phytosynthesis,” uses phytochemicals from plant extracts, such as polyphenols, flavonoids, terpenoids, and alkaloids, to stabilize nanoparticles that are made by reducing metal ions. These compounds act as reducing and capping agents to help nanoparticles form and grow without the need for outside substances. The procedure uses plant materials that are easy to find and plentiful. These ingredients create a wide range of chemical conditions that can change the size, shape, and stability of the nanoparticles. Using plant extracts from leaves, roots, seeds, and fruits, scientists have made nanoparticles of metals like silver and gold and oxides of metals like cobalt oxide. Plant-based synthesis is a good and practical way to make green nanomaterials. It gives you some control over the shape of the particles, reacts quickly, and can be scaled up. Microbial synthesis is the process by which microbes like yeasts, fungi, and bacteria can biosynthesize nanoparticles through metabolic and enzymatic pathways. To turn metal ions into stable nanoparticles, microorganisms release biomolecules and reductive enzymes. Escherichia coli and Fusarium oxysporum are two types of bacteria that can make metal nanoparticles. Microbial synthesis can take longer than plant-based methods since it takes time for microbes to grow and break down. But when you use genetically modified or functionally optimized microbial strains, it gets really selective and specific. Microbial systems can also work in conditions that aren't too harsh, which makes them a suitable candidate for making nanostructures that either interact with or are safe for living things. Biopolymer-assisted synthesis is the third green nanotechnology method. It uses natural polymers like chitosan, cellulose, starch, or alginate as structural templates and agents that help reduce and stabilize things. These materials are very useful in biomedical and pharmaceutical settings since they have certain properties, like being biodegradable, non-toxic, and more biocompatible. Cellulose, which has been used to make metal oxide nanocomposites, and chitosan, which has been used to make silver nanoparticles that kill bacteria, are two examples of these materials. Better control over the structure of nanoparticles usually makes them more stable, easier to spread, and able to do certain tasks. However, making nanoparticles from biopolymers can be harder since you need to regulate how the polymers and metals interact and the exact conditions under which the nanoparticles are made. Each of these green synthesis methods has its own pros and cons, depending on what you want to do with it and what resources you have. Plant- and microbe-based methods can make nanoparticles with a wide range of shapes, while biopolymer-based methods are more likely to give consistent and accurate outcomes. Because microorganisms have limits on how fast they can grow and how they can use energy, plant-based synthesis usually works faster than microbial processes. The specific biopolymer technique depends on the type of polymer and the conditions under which it is made. Because plant-mediated methods include a lot of reactive phytochemicals and an extraction technique that is easy to scale up, they usually make more nanoparticles in terms of yield. The ultimate choice of the green synthesis route must include the desired application as well as the efficiency, cost, environmental impact, and quality of the nanoparticles. This is true whether the goal is catalysis, drug distribution, sensing, or cleaning up the environment. In short, green synthesis of nanoparticles is a long-lasting and environmentally friendly alternative to traditional chemical methods. The three main methods—plant-based, microbial, and biopolymer-assisted—each have their own pros and cons when it comes to yield, size, shape, and reaction time. Biopolymer-assisted synthesis is another approach. It uses natural polymers like starch, chitosan, cellulose, or alginate as reducing agents and building blocks. These polymers' biocompatibility and better control over particle shape make them very useful in biomedical applications. For instance, cellulose nanofibers have been utilized to make stable nanocomposites with metal oxides, and chitosan has been used a lot to make silver nanoparticles that are better at fighting bacteria (Anuradha & Raji, 2022). It is harder to process nanoparticles with biopolymer-assisted technologies, but it gives you greater control over their physicochemical properties, which could make drug delivery and tissue engineering systems more stable and useful. Each green synthesis process has its own pros and cons, depending on the size, qualities, and use of the nanoparticles you want. The table below gives a quick overview of the three primary approaches to make something green:

Table 1 Comparison of Green Synthesis Methods for Nanoparticles

Feature	Plant-Based Synthesis	Microbial Synthesis	Biopolymer-Assisted Synthesis
Reducing Agents	Phytochemicals (polyphenols, flavonoids)	Enzymes, peptides, microbial metabolites	Biopolymers (chitosan, cellulose, starch)
Stabilizing Agents	Same as reducing agents	Microbial secretions	Biopolymer matrix
Reaction Time	Short (minutes to hours)	Moderate to long (days)	Variable (depends on biopolymer and setup)
Size & Morphology Control	Moderate	High (strain-dependent)	High (template-based control)
Yield	Generally high	Moderate to low	Moderate
Scalability	High (due to ease of extract preparation)	Moderate (requires culturing systems)	Moderate (requires controlled processing)
Biocompatibility	High	High	Very high
Application Areas	Catalysis, water treatment, sensors	Drug delivery, antimicrobial coatings, catalysts	Biomedical (drug delivery, tissue engineering)

8. Examples of the Synthesis of green synthesized cobalt oxide NPs

Biogenic synthesis is a better choice than more traditional techniques of making cobalt oxide NPs because it is more environmentally friendly and works better with other materials. Microbes and plants can stabilize NPs by using biomolecules and phytochemicals like flavonoids, proteins, and enzymes. This is a more environmentally friendly way to make NPs than using chemical reagents like stabilizers and reducers. This eco-friendly procedure satisfies the rules of green chemistry because it doesn't make any dangerous chemical byproducts. Figure 3 displays the most frequent ways to make cobalt oxide NPs and stresses how important they are for the environment. Plants and microorganisms give important compounds that act as reducing and capping agents to help make NPs even more. Using this method, cobalt oxide NPs of different shapes, sizes, and properties have been made. Alsaiari et al. (2023) came up with a way to make cobalt oxide NPs that are good for the environment by using a source-based synthesis method.

8.1. Plant extracts (leaves, roots, seeds, bark, fruits, flowers, rhizomes). Different plant fragments, such as leaves,

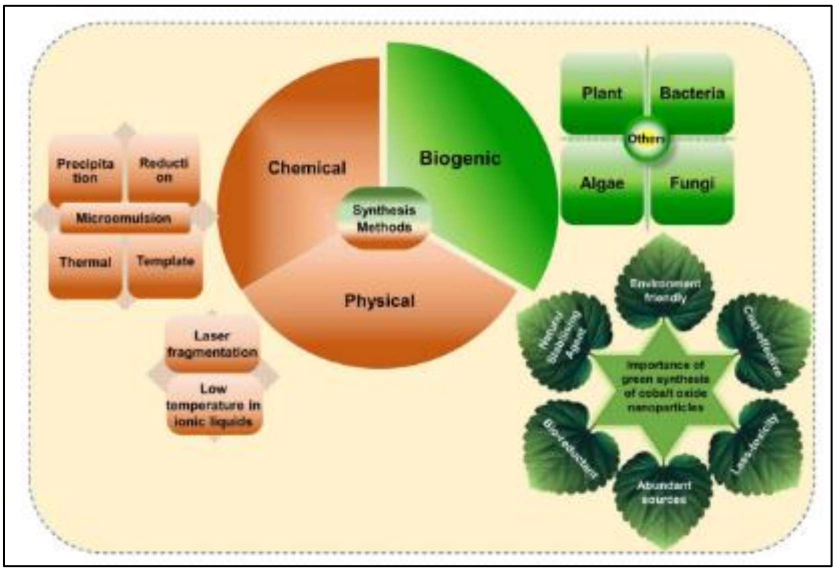

Figure 3 List of common and green techniques for making cobalt oxide NPs and why they are important (Alsaiari et al., 2023)

Using green chemical approaches, cobalt oxide NPs have been made from a number of plant parts, such as fruits, roots, stems, seeds, and flowers. To prepare plant extracts, you need to gather these parts, wash them carefully with distilled or deionized water, and then dry them and either powder them or use them right away. The pieces are then boiled in an alcohol or water bath at temperatures below 60 °C to keep the phytochemicals, which are necessary for NP synthesis. At various temperatures, the extracts, when mixed with a solution of cobalt salts, make it easier to produce cobalt oxide NPs. 92 We didn't need to utilize any extra chemicals during synthesis 87 because the bioactive phytochemicals in the extract work as natural stabilizers and reducing agents (Fig. 3).

8.2. Algae

Algae are used a lot in NP synthesis because they have a lot of natural nano-biofactories that make colors, proteins, carbohydrates, peptides, and secondary metabolites. Eukaryotic organisms called algae live in water. These natural things help bring down and keep the NPs stable. The same methods are used to manufacture algal extract as they are to make plant extracts. The algae are first washed, dried, then ground into a powder. Then, this is combined with distilled water and permitted to sit at 60 °C for four hours. The cooled and filtered extract gets the filtrate added to it. Then, at room temperature, it is mixed with a precursor to cobalt salt. For example, researchers blended an extract from Grateloupia sparsa algae with a cobalt precursor to generate cobalt oxide NPs. When the NPs formed, the combination turned brown instead of pink.

8.3. Fungi

The process of making cobalt oxide NPs is called enzymatic reduction, and it can happen in the cell wall of a fungus or inside the cell itself. Fungi are much better than other microorganisms in making cobalt oxide NPs because they grow quickly and make a lot of NP. This is because these cells have proteins, enzymes, and reducing agents on their surfaces. The first stage is to mix fungus (from bread or somewhere else) with a cobalt salt precursor in a controlled setting (28–30 °C, pH 6.5–11) and let it sit for three to four days. Depending on the precursor used, the color change could progress from yellow to reddish green or even olive green. Enzymatic reduction happens on or inside the cell wall of the fungus, which makes cobalt oxide NPs.

8.4. Microbes or microorganisms

Microbiologically induced precipitation (MIP) is a more environmentally friendly and long-lasting solution than more traditional methods. First, nutrient broth is used to cultivate microbial cultures. After that, the cultures are put in distilled or deionized water. Stir the bacterial suspension and the precursor solution together and let them settle at room temperature. We get the NPs by spinning the mixture at about 5000 rpm for 10 to 20 minutes. After that, the mixture is washed with distilled water a few times. The NPs are dried in a vacuum oven at about 60 °C for 5 to 6 hours, as shown in Fig. 4. How bio-reductants help make cobalt oxide nanoparticles in a way that is good for the environment Bio-reductants that come from natural sources, usually plants, are often used to lower the amount of cobalt metal precursors and keep cobalt oxide NPs stable. Plant extracts that are high in biomolecular compounds, such as phenols, alkaloids, flavonoids, and terpenoids,

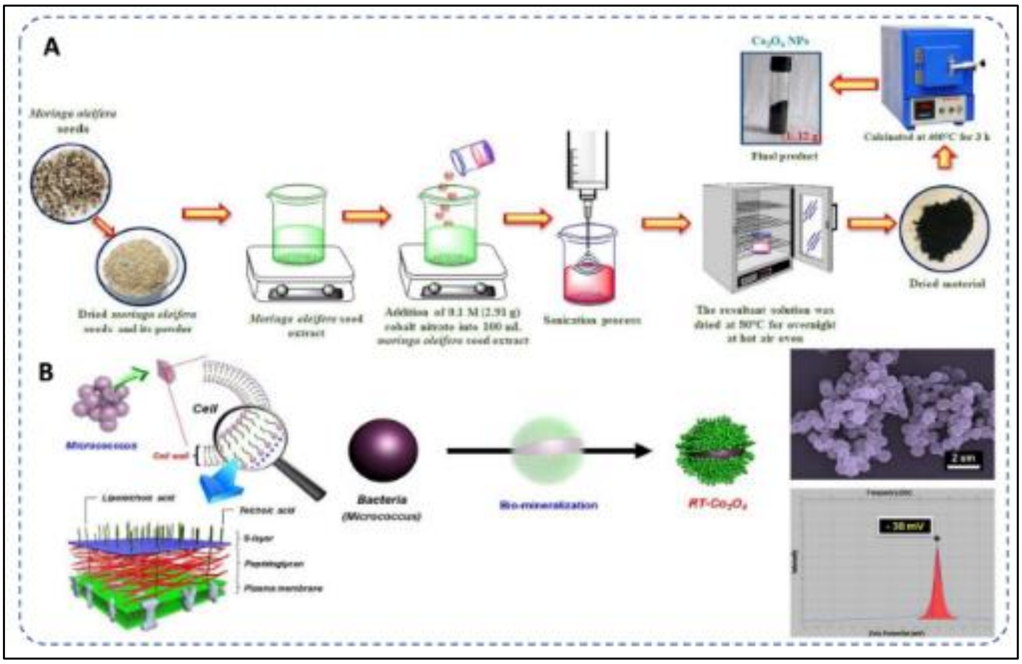

Figure 4 A diagram showing the general steps for (a) making cobalt oxide nanoparticles from plant-based sources (seeds) and (b) making them from microbes (Micrococcus bacteria). (Alsaiari et al., 2023). (Annu et al., 2024)

They have carbonyl (-C]O), hydroxyl (-OH), and carboxyl (-COOH) functional groups that are important for NP stability and reduction (Fig. 4A). When metal ions attach to flavonoids, they break them down into NPs. Other biomolecules keep NPs stable and stop them from clumping together, which affects their form. A lot of plant and microbe extracts are used to manufacture cobalt oxide NP. Some of these are Azadirachta indica, Calotropis gigantea, Curcuma longa, Punica granatum, and many more. Algae have secondary metabolites like proteins, organic compounds (such carbohydrates and polyphenols), polysaccharides, and phytochemicals that have -NH2, -OH, and -COOH functional groups. These chemicals also work as reducing agents. In the same way, bacteria that use bioreduction and fungi that have bioactive substances both help make cobalt oxide NPs, which are safe and renewable alternatives to dangerous chemicals. (Annu et al., 2024) is the source. The steps involved in making cobalt oxide NPs in an environmentally friendly way Phytochemicals like phenolic acids, tannins, flavonoids, and vitamins act as ligands and make plants make NPs. These biomolecules govern the form of the NPs, keep them stable, and keep them from clumping together. 23. These plant chemicals can stick to cobalt ions. Cobalt sulfate, cobalt chloride, cobalt nitrate, and cobalt acetate are the precursors that are most typically used to make cobalt oxide nanoparticles. 17 In situ green synthesis is a single-step process that includes both growth and nucleation. These actions happen with the help of biomolecules contained in extracts. They do this by turning cobalt ions into neutral cobalt atoms, which makes the particles nucleate and stay stable. When these compounds bond with ortho-phenolic hydroxyl groups and ester oxygen atoms, the presence of -OH and -COOH in the phenolic groups shows how strongly they want to react with metals (Annu et al., 2024).

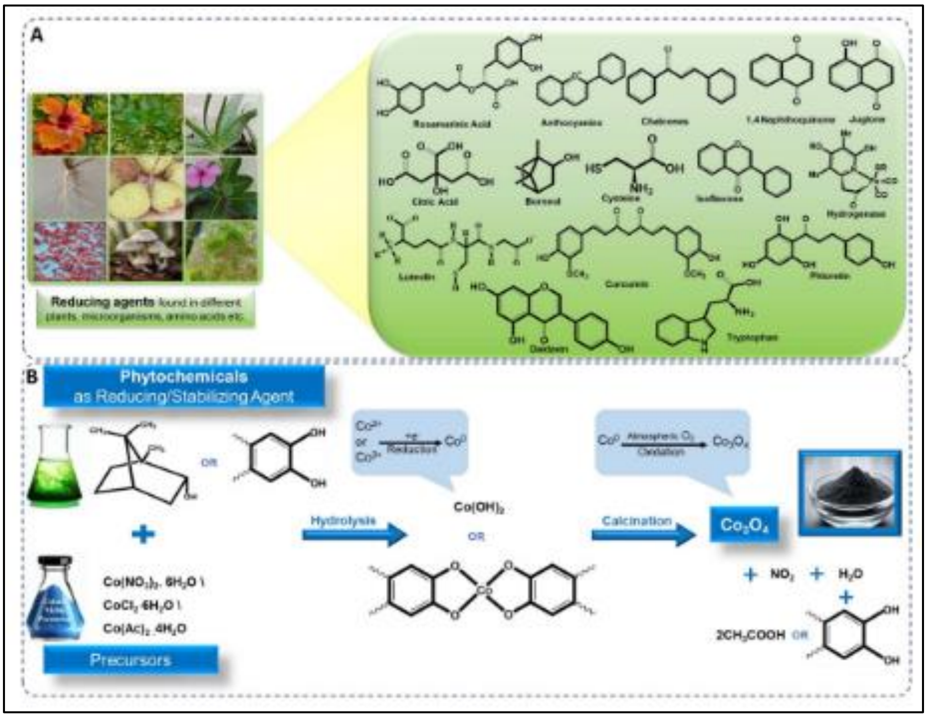

Figure 5 This shows (A) bioreduction and (B) a mechanistic strategy to making cobalt oxide NPs. (Annu et al., 2024)

There hasn't been any direct research on how cobalt oxide precursors affect how reactive these plant-based compounds are. We don't know exactly how that happens, but one possibility is that cobalt oxide precursors could form complexes with phytochemicals. These molecules can both reduce and stabilize, and when they interact with the precursors, they can cause chemical changes that are impacted by temperature and pH. No. 83 They change the stability and degradation rate of plant-based compounds, as well as their solubility and dispersion properties, which affects how reactive they are. 1 Anju et al. (2024) say that cobalt oxide precursors affect both the reactivity of plant-based reagents and the optimized green synthesis process.

Table 2 Comparison of Green Synthesis Methods for Co_3O_4 Nanoparticles

Synthesis Method	Reducing/Stabilizing Agent	Reaction Time	Particle Size	Morphology	Advantages	Limitations
Plant-based synthesis	Phytochemicals (e.g., flavonoids, tannins)	Few minutes to hours	10–50 nm	Mostly spherical	Simple, fast, cost-effective, scalable	Variation in plant extract composition
Microbial synthesis	Bacterial or fungal enzymes/metabolites	Hours to days	20–100 nm	Spherical, rod-like, cubic	High specificity, eco-friendly	Slow growth, risk of contamination, complex setup
Biopolymer-assisted	Natural polymers (e.g., chitosan, starch)	Several hours	15–60 nm	Spherical, irregular	Biocompatible, controlled release, functionalized	Requires purification of biopolymers
Other green methods	Food waste, algae extracts, bio-waste	Variable (hrs–days)	10–80 nm	Varies (depends on source)	Low-cost, waste valorization	Reproducibility issues, less standardized methods

9. Characterization Techniques

Cobalt nanoparticles that are magnetic could be used in a lot of different ways, like as catalysts and magnetic drug targets. This study focuses on making, characterizing, and looking into the catalytic properties and reaction order of magnetic cobalt (Co_3O_4) nanoparticles in the breakdown of hydrogen peroxide. The authors made magnetic cobalt

Co3O4 nanoparticles using the co-precipitation method. Danbature et al. (2023) found that the FT-IR spectra of the Co_3O_4 nanoparticles showed strong absorption peaks at 564.96 cm-1, 662.83 cm^{-1}, 2923.98 cm^{-1}, and ~3532 cm^{-1} and ~3413.61 cm^{-1}. In that sequence, these peaks are the Co-O stretching vibration mode, the O-Co-O bond's bridging vibration, the presence of crystalline Co_3O_4, the -CH3 stretching vibrations, and the -OH stretching and bending modes of water. UV-visible absorption spectroscopy showed a peak at 300 nm. The XRD patterns showed that the Co_3O_4 nanoparticles that were made were not crystalline. The XRD examination of the calcined Co_3O_4 nanoparticle showed that cobalt oxide has a cubic phase structure. The angles (2θ) that stand out the most for the planes 111, 220, 311, 222, 400, 330, and 422 are 18.89°, 31.21°, 36.81°, 38.40°, 44.79°, 49.10°, and 55.65°. We might find out the average size of the Co_3O_4 crystallites by using the Debye-Scherer relation. It was found that Co_3O_4 had a crystallite size of 37.1 nm. Using a Co_3O_4 catalyst, scientists looked into how hydrogen peroxide breaks down into gas at ambient temperature. Increasing the amount of catalyst made the reaction produce more oxygen gas. The breakdown of hydrogen peroxide showed that the Co_3O_4 nanoparticles that were made might be used as good catalysts for breaking down hydrogen peroxide in a lot of industrial and academic settings. According to the study done by Danbature et al. in 2023 People often employ a lot of different state-of-the-art characterization methods to look at the structure, morphology, and functional properties of cobalt oxide (Co_3O_4) nanoparticles. X-ray diffraction (XRD) is a common way to look at nanoparticles to find out things like their crystalline phase, purity, and average size of the crystals. It is easier to see secondary phases, and the spinel structure that is typical of Co_3O_4 is confirmed. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) can help us better understand surface shape and particle size distribution. TEM is better for analyzing lattice fringes and particle aggregation on the nanoscale. Fourier-transform infrared spectroscopy (FTIR) is used to find surface functional groups and confirm the presence of organic moieties in green synthesis, which may leave plant extracts or biopolymers on the surface. It is important to study the optical properties and bandgap energy of Co_3O_4 nanoparticles for photocatalytic and energy-related uses. UV-Vis spectroscopy is a common method for this. Brunauer-Emmett-Teller (BET) surface area analysis looks at the surface area, pore size, and porosity of a material. These are all factors that affect how well it can serve as a catalyst and adsorb. These approaches can be used to fully study the functional potential and physicochemical features of Co_3O_4 nanoparticles made with either traditional or green methods. The shape, size, crystallinity, and stability of biogenically produced cobalt oxide NPs are all important factors to think about when selecting how to use them. These are the basic attributes of these nanoparticles.

9.1. Visual observation, UV-visible and FTIR spectroscopic analysis

It can guess how cobalt oxide NPs will form by looking at the color change in the reaction mixture or by looking at UV-Vis spectroscopy data, which shows big peaks of cobalt oxide NPs between 340 and 500 nm (Fig. 5A(a)). 105 Powdered cobalt oxide NPs that have been made in a lab are a dark olive-green color. People think that the peak at 400 nm is due to surface plasmon resonance. 62 Use a centrifuge to spin the cobalt oxide NPs and the produced NPs at a high speed to separate them. After that, wash them a lot and let them dry at a moderate temperature, like 50 °C. 107 After drying and/or calcination at about 400 °C, the NPs turned into a dark powder. When bacteria like Microbacterium sp. MRS-1 start to make extracellular cobalt oxide NPs, nutrient broth changes from pale pink to dark pink. This is not what happens when other bacteria don't. 106 The cobalt oxide NPs made from the Mollugo oppositifolia leaf extract has a big peak at 3465.93 cm−1. This could mean that there is an N-H group in the amine moiety. We saw signals from alkane C-H functional groups in the range of 2800 to 3000 cm^{-1}. Figure 5A(b)21 shows that the peaks at 509.59 cm^{-1} and 584.80 cm^{-1} confirm the presence of tetrahedral and octahedral CO_2 vibrations, respectively. These peaks show that there are organic biomolecules or surface ligands present because they cause changes in absorption bands that are linked to CO_2 stretching vibrations in metals. The FTIR spectra of Co_3O_4 NPs produced from red algal extract show a large peak about 3500 cm^{-1}. This suggests that there are amide, primary and secondary amine groups, polyphenol, and alcohol groups present because of the bending of OH-NH. Peaks at 1669, 1413, and 1079 cm^{-1} show that the bending of -OH, the stretching of C-O in alcohols and carboxylic acids, and the presence of aromatic rings in plant structures all help make cobalt oxide NPs. Figure 5 A(b) shows that the vibrations of Co^{2+} and Co^{3+} are connected to the peaks at 760 and 562 cm^{-1} in the spectra of Co_3O_4 NPs. When not calcinated, green synthesis makes FTIR spectra show extra peaks that are created by organic functional groups from the biological source that was used (Danbature et al., 2023).

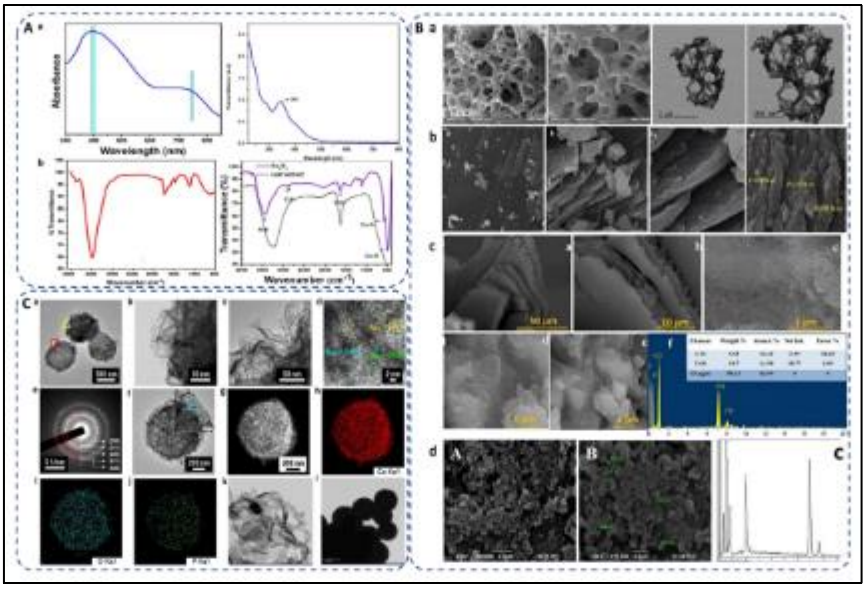

Figure 6 UV-Vis spectra of cobalt oxide NPs made from red sea algae extract (Grateloupia sparsa) and Curcuma longa root extract. (b) FTIR spectra of cobalt oxide NPs made from red sea algae extract (Grateloupia sparsa) and Mollugo oppositifolia leaf extract. (B) SEM pictures of biogenically made cobalt oxide nanoparticles used with (a) Hyphaene thebaica fruit extract, (b) Rosmarinus officinalis leaf extract, (c) Grateloupia sparsa sea algae extract (with EDX), and (d) Microbacterium sp. MRS-1 metal resistant bacteria (with EDX). (C) (a–d) TEM and picture of the microbe-mediated Co3O4 NPs, (e) SAED pattern of porous-Co3O4/bacteria, (f) A TEM picture of a single Co3O4 NP, (g–j) A HAADF STEM picture of cobalt oxide NPs, and (k and l) A TEM picture of sub-spherical cobalt oxide NPs made from rosemary leaves (Danbature et al., 2023)

9.2. Morphology

Green manufacturing methods often use natural bioactive compounds or biomolecules to change the surface of NPs. Researchers can look at the shape, homogeneity, coverage, and aggregation behavior of CO NPs by using SEM to take high-resolution pictures of their surface morphology. This study helps us understand how the NPs interact with their environment, which is helpful for figuring out how green synthesis affects their physical properties and for finding the best synthesis conditions to control their shape so they work the same way in different situations. We looked at the morphology of biosynthesized cobalt oxide NPs with FE-SEM and TEM. For instance, only a few of the porous Co_3O_4 nanorods made by Shim et al. 2017, were open-ended; most of the biosynthesized nanorods were directed by Bacillus subtilis. SEM and TEM studies, as shown in Fig. 5(B and C), showed that the green Co_3O_4 had different shapes. Safdar et al. showed that Co_3O_4 NPs made from Hyphaene thebaica fruit extract have a porous structure. TEM scans showed that the Co_3O_4 NPs made from rosemary leaf extract had a shape that looked like a semi-triangular pyramid. The CoO/Co_3O_4 NPs that Rosmarinus officinalis helped make had a form resembling a sheet. 19 Cobalt oxide NPs made from red algae extract similarly have complex sheet-like shapes. Microbacterium sp. MRS-1 is one type of bacteria that can survive in heavy metals. Sundararaju et al. separated the bacteria from the electroplating industrial effluent so that they could turn the cobalt metal into cobalt oxide NPs and clean up the wastewater. SEM-EDX examination showed that the clumped Co_3O_4 NPs exhibited a 54:34 Co:O elemental ratio and sizes that ranged from 10 to 70 nm (Fig. 6B(d)).

9.3. Size

DLS analysis, transmission electron microscopy, and XRD are all common ways to tell the size of biogenically generated cobalt oxide NPs. You may find the average crystallite size of cobalt oxide nanoparticles by looking at the XRD peaks and using the Debye-Scherrer equation (1) (ref. 21). Equation (1) says that the average crystallite size, or D, is equal to the form factor, l, the wavelength of X-ray radiation, b, and the cosine of Bragg's angle. According to Raimundo et al.110, cobalt oxide NPs produced by Rhodophyta were about 65 nm in size on average. We generated nanocrystals that were 6.7 nm and 2–5 nm in size from the latex of *Calotropis procera* and the leaf extract of *Ipomoea carnea*. We found that cobalt oxide NPs made from Aerva javanica (a plant), Bacillus subtilis (a bacterial strain), and *Fusarium oxysporum* (a fungus) had particle sizes of 39.23 nm, 31.2 nm, and 33.4 nm, respectively. 85 When the NPs made from Arista leaves extract are heated to a high annealing temperature of 800 °C, they quickly grow to a size of 39.44–53.56 nm. Shim et al. used *Micrococcus lylae* bacteria to make Co_3O_4 NPs that had crystalline sizes between 2 and 10 nanometers and formed mesoporous structures (Fig. 5C(a-j)). Because they are so small, Co3O4 NPs can more easily go through bacterial membranes. Smaller nanoparticles work better as antibacterial agents since they spread out more evenly and don't stick together as much. Once inside a cell, they can boost their ability to kill bacteria by messing with two basic cellular processes: DNA replication and enzyme activity. Akhlaghi et al.114 Co_3O_4 NPs had a hydrodynamic diameter of 218 nm, which is bigger than the SEM size of 6-20 nm. This is probable because there are layers of water molecules on the surface of the cobalt oxide NPs. This diameter is very important for stability and spreading out. The DLS analysis indicated that the total size of the 20 NPs made from Geranium wallichianum was 320 ± 2.33 nm. Also, 26 NPs from *Ipomoea carnea* were found to be between 4 and 10 nm, with an average size of 7.83 nm. Figure 6A(a) reveals that the 104 DLS examination of NPs made by red algae showed that they were 48.1 ± 5.32 nm in size. The average size of 62 cobalt oxide NPs made with Moringa seed extract was 44.51 nm, while the average size of chemically made NPs was 41.10 nm (Fig. 6A(b)). According to the study done by Danbature et al. in 2023

9.4. Surface interface:

The chemical structure and characteristics the surface of the NP has a big effect on how useful it is. We employ Brunauer-Emmett-Teller (BET) methods to find out the surface area of bio-inspired cobalt oxide NPs. For instance, it was said that the cobalt oxide NPs in the Calotropis gigantea plant had a BET surface area of 46.7 $m^2\ g^{-1}$. In general, NPs with a large surface area have more active sites and adsorbed substrates, which makes them better for the catalytic reaction you want. Recently, silica gel made from rice husks was used to make 91 cobalt oxide NPs with a surface area of 735 $m^2.g^{-1}$. The surface area of this is bigger than that of the Co_3O_4/MCM-41 nanocomposites, which had a surface area of 608 $m^2.g^{-1}$. X-ray photoelectron spectroscopy (XPS) and Raman spectroscopy can tell you the elemental composition and oxidation states of cobalt, as well as the chemical bonds or vibrational modes that are connected to the crystal lattice on the surface of the NP. For example, the XPS peak of Co2p with O1s consistency and binding energies of 2p1/2 and 2p3/2 at 779.4 and 794.3 eV, respectively, can be seen in cobalt oxide NPs that were made with the help of the *Aspalathus lineari* plant extract (Fig. 6B(a)). Vinayagam et al. also reported that cobalt oxide NPs had two overlapping peaks for the Co^{3+} and Co^{2+} oxidation states, with a 16.11 eV gap between them. This was because the binding energies were 797.13 eV (Co 2p1/2) and 781.02 eV (Co 2p3/2). The O 1s peak at 531.28 eV is very broad, which means that it can bind to both of cobalt's oxidation states. Also, a C 1s signal at 284.81 eV (Fig. 6B(b)) shows that the organic parts of the extract are involved.

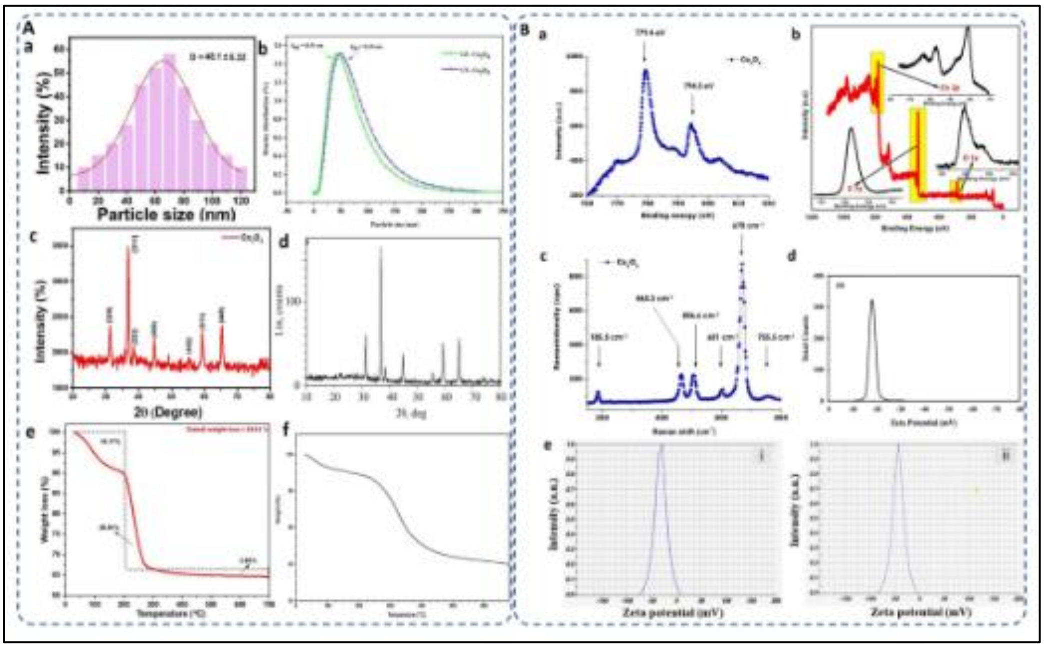

Figure 7 (A) DLS analysis of the size distribution of biosynthesized cobalt oxide NPs made from marine red algae and Moringa seed extract; (c and d) XRD pattern of cobalt oxide NPs made from Mollugo oppositifolia L. leaf extract21 and gelatin;115 (e and f) TG curve of Muntingia calabura116 and bacteria-mediated (Microbacterium sp. MRS-1) biosynthesized cobalt oxide NPs. (B) (a and b) XPS of Aspalathus linearis plant extract117 and Muntingia calabura leaf extract116 that helped make green synthesized cobalt oxide NPs; (c) Raman spectra of biosynthesized annealed cobalt oxide NPs;117 (d and e) zeta potential of Rosemary extract; and (e) lemon extract29 that helped make green synthesized cobalt oxide NPs

9.5. Stability

TGA and zeta potential can be used to test the thermal and colloidal stability of biogenically produced cobalt oxide NPs, along with other important factors. For instance, the NPs made from *Muntingia calabura* leaves lost 38.91% of their weight between 28 and 300 °C. This could be because the leaves broke down and lost moisture. At 300 °C, there was a 2.83% loss, which could mean that the phase changed from CoO to Co_3O_4 (Fig. 7 A (e)). The cobalt oxide nanocrystals mixed with gelatin were shown to be durable since they lost water between 50 and 110 °C, burnt biologically at 350 °C, and made pure cobalt oxide between 350 and 460 °C. The nutrients made by the *Grateloupia sparsa* algae broke down naturally at a rate of 6.3% at 260 °C and 17.6% at 410 °C. The NPs made by 82 and *Microbacterium* sp. MRS-1 lost 7% of their mass at 100 °C, 15% at 225 °C, and 50% between 250 and 400 °C. However, these NPs stayed stable up to 700 °C (Fig. 7A (f)). 106 The negative zeta potential of -20.4 mV in NPs from *Trigonella foenumgraceum* showed that there were surface hydroxyl groups. This showed that the NPs were stable in a colloidal state. The positive zeta potential of -18 mV in NPs made from rosemary leaves (Fig. 6B(d))20 showed that the NPs were also stable in a colloidal state. The zeta potentials of −10.5 mV and −40 mV for the NPs made from Geranium wallichianum and Cordia myxa, respectively, suggest that they include phytochemicals that help them spread out and keep them from clumping together. The peptidoglycan in Bacillus subtilis-mediated porous NPs also caused them to have −46 mV. Figure 7B(e) indicates that NPs made from lemon extract had an even higher zeta potential of −33.4 mV when not heated and −42.1 mV when heated, which means they would strongly repel each other and be stable. Higher zeta potential levels make electrostatic repulsion, stability, and the rate of medium aggregation all better. Cobalt oxide NPs are more stable than chemically made NPs because the functional groups of biomolecules act as natural stabilizers and offer the surface charge that impacts the zeta potential directly. A review of the literature on cobalt oxide NPs that are good for the environment 4.1 Using organic materials It is now possible to make cobalt oxide nanoparticles (NPs) in an environmentally benign way using extracts from many different plants. This has opened up a lot of new uses for these nanoparticles. For instance, Cirsium vulgare leaf extract showed catalytic activity in the oxidation of L-cysteine and generated NPs that were around 20 nm in size on average. To get very good repeatability in H_2O_2 detection, we made monocrystalline spinal cobalt oxide NPs by biochemically lowering CoOOH to $Co(OH)_2$ using an extract from the *Sechium edule* fruit. 122 The cobalt oxide NPs made from the Ipomoea carnea extract stopped Staphylococcus aureus and Shigella flexneri from growing in areas of 17.8 nm and 16.7 nm, respectively. These are similar to the medicines ampicillin and vancomycin. The NPs are 6.78 nm wide. Bronzato et al. made 4.5 nm cobalt oxide quantum dots (QDs) from tomato seed extract, and these QDs were good in breaking down Ciprofioxacin. Rosemary leaf extract, which is high in carnosol, carnosic acid, rosmanol, isorosmanol, and caffeic acid, made cobalt oxide NPs that were very good at attacking cancer cells, especially Gep G2 and MCF7. You can get cobalt oxide NPs from many different plants. Using algae are becoming more and more popular for green synthesis applications, such the biological synthesis of NPs, since they grow quickly, are easy to collect, and are cheap to scale up. A one-pot hydrothermal process can be used to make cobalt oxide NPs from an extract of the marine red algae *Grateloupia* sparsa. These NPs can then be used in supercapacitors. This red algae extract has a reducing impact since it contains carbohydrates, lipids, proteins, antioxidants, and pigments including phycobilins and chlorophylls.

10. Applications

There have been reports of different types of NP and how they are used in medicine, cosmetics, electronics, optics, energy generation, and environmental science. The silver nanoparticle (AgNP) is an example of an NP. It may be found in a lot of various metals and alloys. Copper, gold, silica, platinum, palladium, zinc oxide, magnesium oxide, cerium dioxide, and titanium oxide are some other examples of NPs. Cobalt and cobalt oxide (Co_3O_4) NPs have been used a lot in several fields since they are very useful and have unique features. Co_3O_4 is an antiferromagnetic p-type semiconductor with a straight optical band gap between 1.48 and 2.19 eV. Co_3O_4 can be used for many things, as seen in Figure 7. These include gas sensors, solar selective absorbers, energy storage, pigments and dyes, field emission materials, capacitors, heterogeneous catalysis, magneto-resistive devices, gas sensors, and biomedical applications (such as antibacterial, antiviral, antifungal, antileishmanial, therapeutic agent, anticancer, and drug delivery). Only cobalt oxides, including Co_3O_4 and CoO, are stable in nature. Among these, Co_3O_4 is the most stable. This review is about cobalt and cobalt oxide nanoparticles (NPs) and focuses on how they are made, how they are characterized, and what they do in living things.

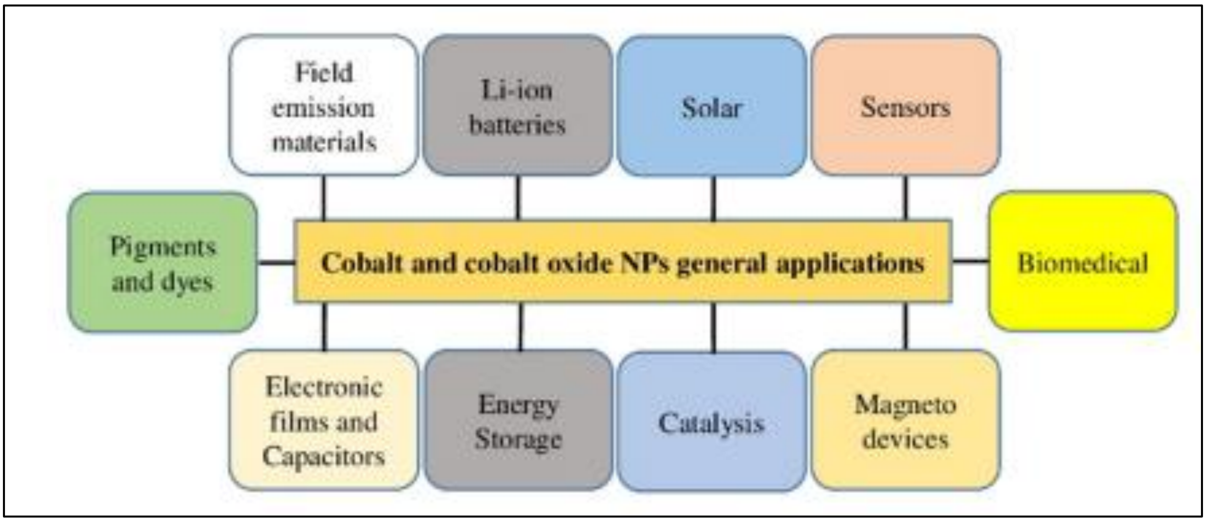

Figure 8 General applications of cobalt and cobalt oxide NPs

Some of potential biological uses of environmentally friendly cobalt oxide nanoparticles:

10.1. Antimicrobial efficacy

Antimicrobial activity is the ability to kill or limit the growth of microorganisms without harming adjacent tissues. Plants have secondary compounds that stop microbes from growing. This makes green-made NPs work better than regular NPs. distinct kinds of plants may have distinct antibacterial effects from cobalt oxide nanoparticles made from plants. There are several ways to test the antimicrobial activity of plant extracts, including the disc diffusion method, well diffusion, time-kill assay, agar dilution, broth dilution, and many more. Disc diffusion and well diffusion are the two most prevalent methods. We will talk about a lot of different types of antimicrobial activity in this part, such as antifungal and antibacterial activity.

10.2. Activity against bacteria

Bacterial infection is the most common cause of death from infectious diseases. Recent advances in nanotechnology may soon make it possible for a mm-thick lipopolysaccharide coating to keep germs away. When Gram-positive bacteria burst, they die faster because their cell walls are thinner. We employed the disc diffusion method to test how well cobalt oxide NPs, which are tiny and have a high surface-to-volume ratio, kill E. coli and S. aureus bacteria. The results showed that the nanoparticles produced higher reactive oxygen species (ROS) at 25 mg ml^{-1} and 50 mg ml^{-1}, which caused a high zone of inhibition of 10.5 mm and 8.3, 11.6 mm, respectively. Figure 7B(d) indicates that the extract of Aerva lanata leaves had antibacterial effects on the bacteria E. coli, S. typhimurium, P. vulgaris, and S. aureus when it was used to make cobalt oxide NPs in a green way. The disc diffusion approach was used.

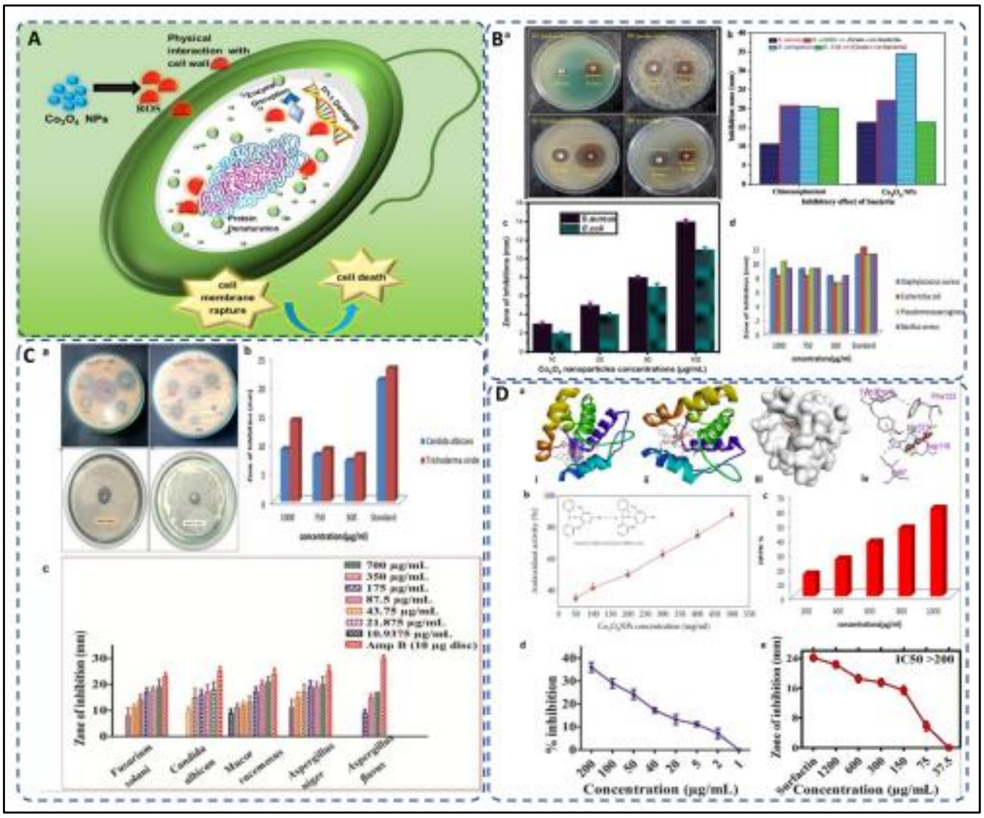

Figure 9 (A) The general way that biogenic cobalt oxide NPs kill cells; (B) The antimicrobial activity of green synthesized CO_3O_4 NPs against (a) S. aureus, B. subtilis, P. aeruginosa, and E. coli; (b) The inhibitory effect of Co_3O_4 NPs compared to standard chloramphenicol; (c) The effect of Curcuma longa plant extract against S. aureus and E. coli; and (d) The effect of Aerva lanata at different concentrations. (C) Cobalt oxide NPs kill fungi (a) A. favus, A. niger, A. niger, C. albicans, (b) Candida albicans and Trichoderma viride, 127 (c) by Geranium wallichianum at different levels. 26 (D) (a) Docking experiments of green produced cobalt oxide NPs demonstrating (i) helical structure, (ii) molecular surface, (iii) 3D display, and (iv) binding interaction with binding sites of 3OGN protein. Antioxidant activity of biogenically generated cobalt oxide NPs by (b) Grateloupia sparsa (inset reduction of DPPH82) and (c) Aerva lanata at different levels. (d) the ability of Geranium wallichianum leaves extract to stop the action of the amylase enzyme, and (e) the ability of Rhamnus virgata leaf extract to stop the action of protein kinase

10.3. Larvicidal activity and docking studies

Recent work by Gowthami et al. utilized an aqueous leaf extract of *Mollugo oppositifolia* L. as a bioreductant to study the parasitology of green produced cobalt oxide NPs against Culex quinquefasciatus, a species of urban mosquito larva. Table 8 shows that the biosynthesized Co_3O_4 NPs outperformed the aqueous plant extract and permethrin in terms of their larvicidal efficacy, with an LD50 value of 34.96 mg ml−1. 21 Likewise, compared to the control, permethrin, the docking experiments of green generated Co_3O_4 NPs with the larvicidal odorant 3OGN binding protein showed a significant binding affinity of -8.5 kcal mol−1. Given that hydrogen bonding is the driving force behind the protein-ligand binding interaction, it follows that the distance between the hydrogen donor and acceptor bonds should not exceed 3.5 Å. 21 In this instance, the greenly generated Co_3O_4 NPs show three hydrogen bond interactions with the larvicidal mosquito 3OGN protein. The distances of these interactions are 2.10, 1.63, and 1.98, respectively, and are attributable to amino acids Asp118, His121, and Phe123 (Fig. 7D(a)). 21 Because of their capacity to produce reactive oxygen species (ROS) and interfere with cellular function in larvae, green cobalt oxide NPs display strong larvicidal action, especially against mosquito larvae. They can replace chemical pesticides because they are less harmful to the environment.

10.4. Antioxidant activity

When free radicals destroy lipids, DNA, and proteins, it can lead to diseases including cancer and heart issues. The body makes free radicals all the time. The antioxidants in the plant or microbial extract lessen these bad effects. Cobalt oxide NPs stops radical chain events by donating electrons to free radicals. It has been observed that the antioxidant activity of green-made cobalt oxide NPs rises with higher concentrations, as shown by their ability to scavenge DPPH.

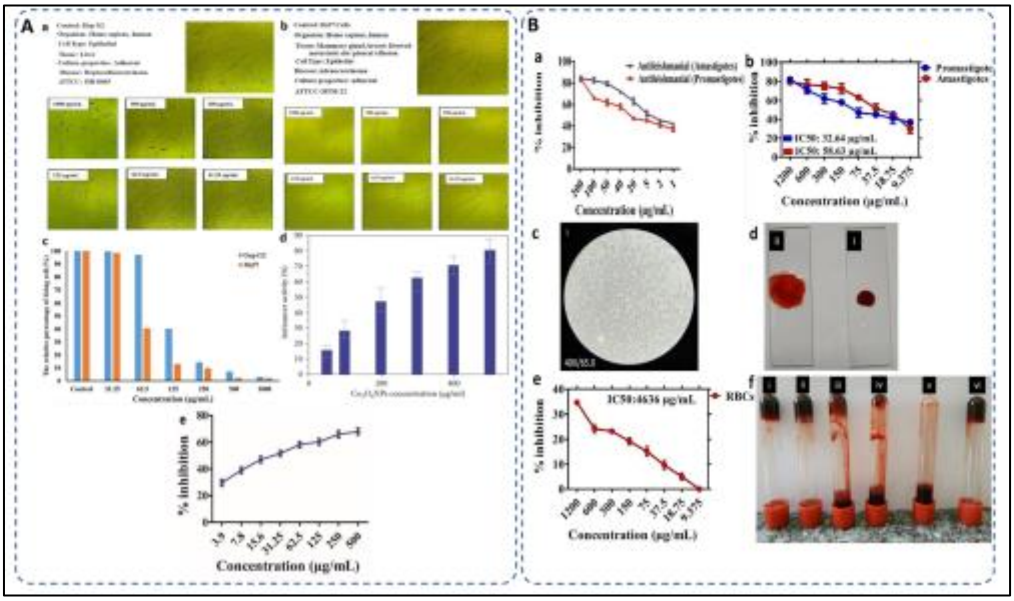

Figure 10 (A) Microscopic pictures of (a) Hep G2 and (b) Mcf7 cancer cells after being treated with different amounts of Co3O4 NPs made from rosemary leaf extract (c) The percentages of live Hep G2 and Mcf7 cancer cells after being exposed to different amounts of Co3O4 NPs made from rosemary leaf extracts,20 (d) how well cobalt oxide NPs kill HepG2 cancer cells 82 (e) harmful to the HepG2 cancer cell line. (B) The antileishmanial activity of (a) G. wallichianum and (b) cobalt oxide NPs helped by Rhamnus virgata at varied concentrations. (c) Microscopic pictures of biosynthesized cobalt oxide NPs in red blood cells that don't cause as much hemolysis. (d) The ability of biosynthesized cobalt oxide NPs to break up blood clots; (e) the ability of Rhamnus virgata-mediated cobalt oxide (CoO) NPs to break down red blood cells; and (f) the ability of green produced cobalt oxide NPs to stop blood from clotting

10.5. Enzyme inhibition

Enzymes that can cause long-term health problems if not controlled have shown promise as blockers of cobalt oxide (CoO) NPs made from green plants. Recent studies have looked into techniques to stop the a-amylase enzyme from working. This can help lower blood sugar levels and minimize the risk of diabetes. At 1 mg ml−1, CoO NPs made by G. wallichianum did not stop anything, but at 200 $mg.ml^{-1}$, they were able to stop 36% of the time (Fig. 9 D(d)). There were 25 ml of enzyme, 15 ml of PBS, 40 ml of starch solution, and 10 ml of cobalt oxide NPs in the reaction. The mixture was heated to 50 °C for 30 minutes, and the controls were distilled water and acarbose.

10.6. Effectiveness against cancer

Cancer is the leading cause of mortality in the world, killing around 10 million people each year. Between 2020 and 2050, the disease will cost an estimated $25.2 trillion. Cobalt oxide NPs are getting more attention as a possible low-cost alternative to traditional anticancer medications since they are cytotoxic, ferromagnetic, and less poisonous. Multiple investigations have found that the toxicity of these metal oxide NPs depends on their content, how they are given, and the cells or creatures they come into contact with. On the other hand, eco-friendly methods can make the toxicity of cobalt oxide NPs less harmful. The toxicity of cobalt oxide NPs may change depending on the dose. 79 One study looked at the ecotoxicological effects of cobalt oxide NPs made in ways that are good for the environment. The results showed that these NPs were typically very low-toxicity and did not pose a hazard to ecological systems. These NPs are safe for living things and can be used in a variety of ways, including in medicines. This is because their toxicity only goes down at very high concentrations, like 750 mg per disc, as mentioned. Most studies that are relevant to this don't look at how harmful something is. But other studies, like those that look at cytotoxicity and hemolysis, let us look at their toxicity and come up with a theory about it.

10.7. For wastewater treatment

This study combined co-precipitation synthesis of natural clay (NC) with Co_3O_4 nanoparticles (NPs) to make super NC@ Co_3O_4 nanocomposites. These can get rid of heavy metal pollution like toxic Pb(II) and Cd(II) ions. The nanocomposites were very resistant to salt, stable in the environment, and could be used again and again. Using the NC@ Co_3O_4 adsorbent has two benefits: it is biocompatible and easy to make. In addition, NC@ Co_3O_4 is able to keep its excellent adsorption ability by taking into account a number of environmental conditions, such as the solution pH, the NC@ Co_3O_4 dose, the length of the adsorption process, and the beginning concentration of heavy metals. To confirm the synthesis and characterisation of NC@Co3O4 nanocomposites, several tests were done, including FTIR, XRD, TGA, SEM-EDS, TEM, and AFM. Researchers found that NC@ Co_3O_4 nanocomposites could absorb up to 86.29% of Pb(II) ions and 82.06% of Cd(II) ions. When tested on NC@Co3O4 nanocomposites for water adsorption, the highest amounts of Pb(II) and Cd(II) that could be adsorbed were 55.24 and 52.91 mg/g, respectively. The PSO kinetic model fit the kinetics data well, and the theoretical Langmuir isotherm model and the equilibrium adsorption model agreed well. Monte Carlo (MC) simulations showed that this adsorption happened on its own because Eads had negative values. The MC simulations that looked at how the surfaces of NC@ Co_3O_4 nanocomposites interacted with heavy metal ions gave results that were quite similar to those of the tests. The study found that NC@Co_3O_4 nanoadsorbents are great for cleaning up wastewater because they have unique properties that make them good at adsorbing pollutants and can be used in a wide range of situations (El Mouden and others, 2023). This method for measuring molecular interactions uses a random mix of species (ions and molecules) that are kept in a simulation box. Figure 7 illustrates how much energy it takes for lead and cadmium ions to stick to the quartz-Co_3O_4 surface and the dolomite-Co_3O_4 surface. The Eads values for Pb(II)-dolomite-Co_3O_4, Pb(II)-quartz-Co_3O_4, Cd(II)-dolomite-Co_3O_4, and Cd(II)-quartz-Co_3O_4 were − 577.1, − 630.35, − 706.25, and − 769.65 kcal/mol, in that order. Jafari et al. (2022) say that these results mean that heavy metal ions naturally stick to NC@Co_3O_4. Figure 10 also shows how to figure out the shape of heavy metal ions on the simulated surfaces. The final shape of MC further supports this idea because it plainly demonstrates that metal ions are close to the surface. (Latino et al., 2023)

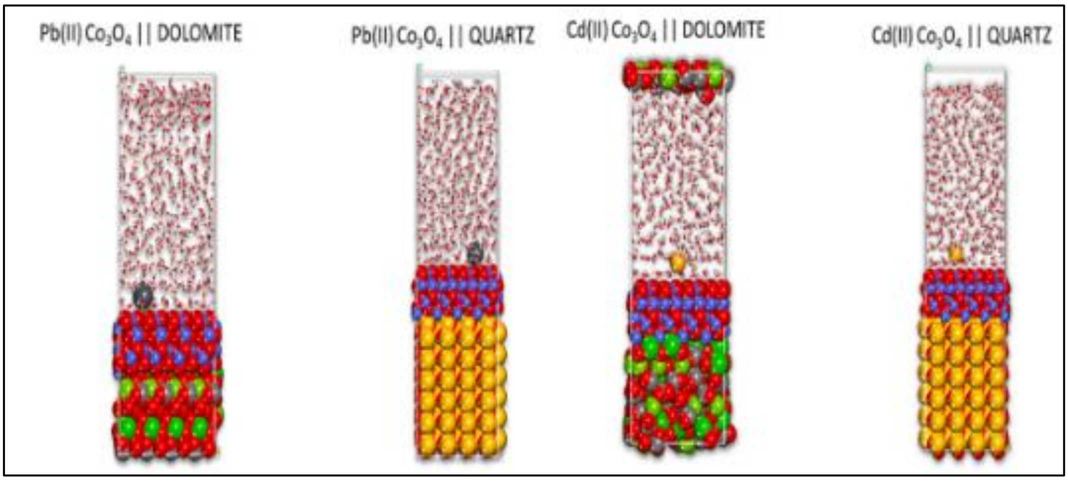

Figure 11 Geometry of lowest energy poses obtained after MC for Pb(II) and Cd(II) ions on modelled surfaces of dolomite-Co3O4 and quartz-Co3O4 surfaces. (El Mouden et al., 2023)

Govindasamy et al. (2022) say that nanoscience and nanobiotechnology are becoming more significant in cancer treatment to make treatments more effective and less harmful to cells. Chemotherapy, radiation, and many more drugs have been used a lot in cancer treatment to try to kill all the cancer cells. The results of these methods are not good because any residual cells keep proliferating and turning into new cells. To solve these problems, a lot of people have turned to nanoparticles and nanotechnology. Cobalt oxide nanoparticles were made from the water extract of P. guajava. The obtained P. guajava Co_3O_4 NPs were characterized by UV-visible spectroscopy, FTIR, XRD, SEM, and EDAX. The UV-Vis test shows that there is a clear absorption peak at 286 nm. The FTIR study showed that the P. guajava Co_3O_4 NPs included both alcohol and amide groups. The XRD patterns showed that the P. guajava Co_3O_4 NPs produced from green are all crystalline. The SEM-EDAX test showed that the synthetic P. guajava Co_3O_4 NPs were shaped like spheres that were stuck together. The P. guajava Co_3O_4 NPs showed very good antioxidant DPPH and ABTS scavenging activities. The active photocatalytic capabilities of the P. guajava Co_3O_4 NPs helped break down straight blue 71. The MTT test demonstrated that P. guajava was harmful to cells. The amount of Co_3O_4 NPs affected the dosage. The half maximum inhibitory concentration (IC50 value) for HCT 116 cells was 24.5 μg/mL, and for MCF-7 cells, it was 29.5 μg/mL. P. guajava Co_3O_4 NPs killed more HCT 116 colorectal cancer cells than MCF-7 breast cancer cells, which means they could be utilized to treat different types of cancer. “Various Applications of Nanomaterials” is what Alsaiari et al. (2023) say. There are many ways to use green-synthesized NMs in physics, chemistry, and biology. They could be used in biology for things like delivering drugs, bioimaging, biosensors, and recognizing biomolecules. These green-synthesized NMs can help with the biological activities of everyday things including humidifiers, water purification systems, deodorant, toothpaste, cosmetics, and more. You can also store energy in oxide and solar batteries. NMs are very important in farming because they help keep nutrients in the soil and find and get rid of plant diseases, both of which boost crop yields. Nanotechnology also provides a lot of new ways to cut down on pollution in many different kinds of work. For example, it can be used to replace plastics with biodegradable materials and get rid of harmful chemicals from production processes. It can also help keep the world's clean water supplies safe by cleaning up water that has been polluted with heavy metals, dyes, and drugs. Because of this, nanotechnology is and will continue to be a hot topic of conversation. This is because both academics and policymakers are hopeful that this technology can help solve important problems now and in the future. Figure 11 shows the several areas where nanoparticles are used.

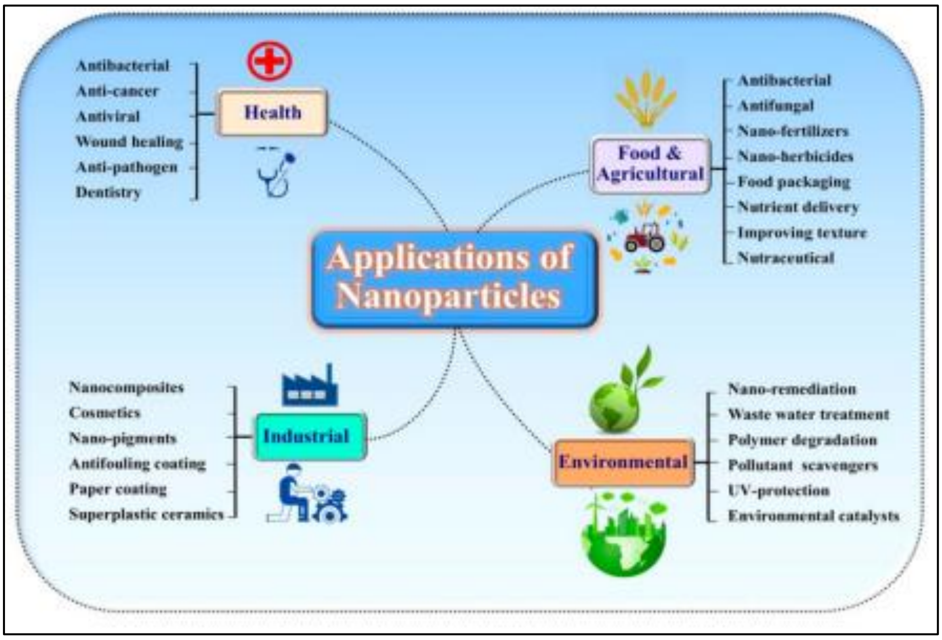

Figure 12 Use of nanoparticles in different fields. Copied from MDPI (Ali et al., 2020)

How to Treat Water Pharmaceuticals, dyes, heavy metals, and other dangerous chemicals are now getting into water supplies all around the world (Vardhan et al., 2019). When contaminated wastewater is dumped directly into water sources, it pollutes those sources with the toxins. One way to fix this problem is to clean up the wastewater before letting it out. When it comes to treating water, traditional approaches have their problems. For instance, they don't always get rid of all the contaminants, and they take a long time to work. Nanoparticles (NMs) that are good for the environment are a good way to clean up dirty water. Many NMs have been used in water purification. Researchers have made magnetic iron oxide (Fe_3O_4) nanoparticles using methods that are suitable for the environment and cheap (Bibi et al., 2019) so that they can break down organic colors using photocatalysis. Using the seed extract of pomegranate (Punica granatum), nanoparticles that are semi-spherical and evenly spread out in the size range of 25–55 nm have been made. When exposed to ultraviolet light, the Fe_2O_3 nanoparticles showed amazing photocatalytic activity against reactive blue dye, breaking it down by 95.08% in just 56 minutes. In the same way, iron oxide nanoparticles have been made by using the leaves of the papaya plant (*Carica papaya*). The results demonstrated that MgO nanoparticles made from biogenic sources could be useful for breaking down organic dyes in wastewater. Figure 8 shows a general way that nanoparticles like Fe_3O_4, Fe, Ag, and Au can break down different dyes using light.

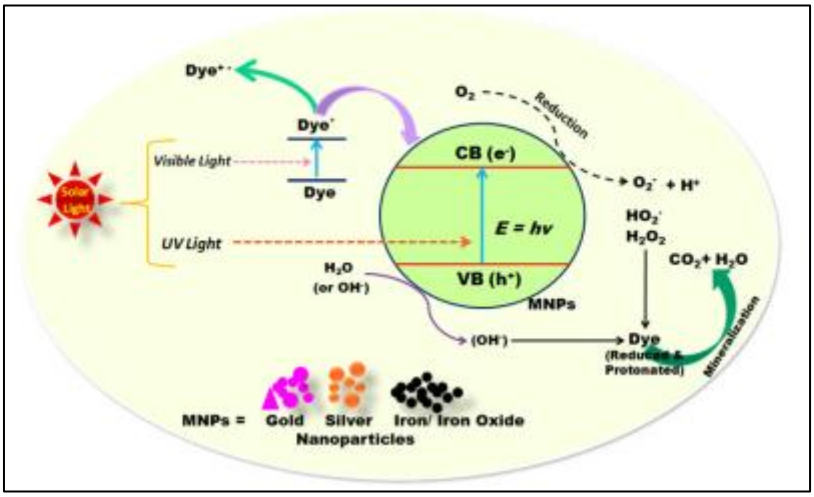

Figure 13 Possible mechanism for the photocatalytic degradation of different dyes using nanoparticles. Copied from MDPI (Abedelaziz et al., 2023). (Kumar et al., 2021)

Also, nanoparticles that are good for the environment have been employed to get rid of hazardous metals. We made spherical TiO2 nanoparticles that are 10 nm in size using a method that is safe for the environment, cheap, simple, and not harmful. The leaf extract of *Syzygium cumini* was used as the capping agent. Researchers looked examined these nanoparticles to see how well they could remove lead (83%) and lower COD (75.5%). Researchers in a separate work were able to make TiO_2 nanoparticles by using the polyphenolic tannins found in *Jatropha curcas* L. leaf extract as a capping agent. Mathew et al. (2017) say that wastewater that has chemical and dye residues in it needs to be treated adequately before it can be sent out into the environment. You can't get rid of most of these dyes with physical or biological methods. So, photo-catalyzed degradation is regarded to be the best way to treat these dyes and chemicals. The goal of this lab project was to look into how Co_3O_4 can break down wastewater by photo catalytic degradation and to make Co_3O_4 utilizing the co-precipitation method. We looked examined the photocatalyst's characteristics using a particle size analyzer, XRD, and scanning electron microscopy. The results show that the co-precipitation method can be utilized to make Co_3O_4, and that photocatalytic degradation of wastewater can be done in just 120 minutes. After making the cobalt oxide, the wastewater was used to treat the photocatalyst. A solution of methylene blue dye with a concentration of 10 mg/l was used to remediate wastewater. Put 0.1 g of nanoparticle cobalt oxide in a beaker with 100 mg/l of methylene blue dye and let the sun shine on it to clean wastewater. The cobalt oxide photocatalyst completely got rid of the blue color of the methylene blue dye in the wastewater in just two hours. So, the cobalt oxide nanoparticles that were made started to work. We examined the cobalt mass and concentration in soil that had been polluted with different things on the main crop, spring barley (Hordeum vulgare L.), and the after-crop, white mustard (*Synapis alba* L.) (Kosiorek et al., 2020). Manure, charcoal, clay, zeolite, and calcium oxide were all used to stabilize the plants. We added cobalt chloride to the soil at levels of 0, 20, 40, 80, 160, and 320 mg/kg. We added manure, clay, charcoal, and zeolite to 2% of the soil's weight in a container. We also added 1.30 g of calcium oxide per kg of soil. At the highest doses of cobalt, the plant output and tolerance index for cobalt went down a lot. Soil cobalt contamination went up, which caused the amount of cobalt in plants to go up a lot and the cobalt translocation factor to go down. Phytostabilization amendments had a big effect on the growth, development, and cobalt content of oats. Calcium oxide (white mustard) and manure (both plants) had the biggest effect on the output of the above-ground parts. Zeolite (white mustard) and calcium oxide (both plants) had the biggest effect on the weight of the roots. Adding things to the soil, including manure, zeolite, and calcium oxide, made both plants more tolerant. Clay, on the other hand, had no effect on either plant. All phytostabilization chemicals, except zeolite, lowered the amount of cobalt in the roots of spring barley and in the parts of the plant that are above ground. The cobalt levels went down in both parts of the white mustard plant. In the manure and zeolite, the levels went down in the above-ground parts, and in the calcium oxide, they went down in both parts. Calcium oxide lowered the amount of cobalt in the roots of both plants, especially in the roots of spring barley. Most of them also lowered the amount of cobalt that was bioconcentrated in parts of the plant that were above ground. The effect on cobalt translocation wasn't as clear, although most phytostabilization chemicals made it easier for cobalt to move from the soil to the plant. White mustard could hold more cobalt than spring barley. Viljoen et al. (2021) made the cobalt oxide nanoparticles using a precipitation-oxidation process that took place at low temperatures. TEM and XRD showed that the nanoparticles were round and had sizes between 4.6 nm and 19.4 nm. The XRD test showed that the nanoparticles were made up entirely of the Co_3O_4 phase. We utilized different amounts of hydrogen peroxide, an oxidant, to control the size of the nanoparticles. Without molecules that cap the molecules, the size was kept in check. The yield went up when the amount of hydrogen peroxide went up. The cobalt oxide nanoparticles sped up the Fenton reaction, which broke down the methylene blue dye by oxidizing hydrogen peroxide. The smaller the particles, the more catalytic activity they have. The nanoparticles, which were 4.6 nm in size, acted as a catalyst and caused 99% of the material to break down in under 30 minutes. Without the catalyst, methylene blue did not seem to break down at all.

11. Enhanced activity of green synthesized cobalt oxide NPs

Cobalt oxide NPs made from green materials may be more active if they have better crystallinity and a form that can be regulated. Plant extracts can add biomolecules to the surface of NPs in a way that is good for the environment. These molecules can be carboxyl, hydroxyl, or amino groups. Functional groups can make reactants interact better and raise the amounts of some properties. During the production of NPs, biomolecules included in plant extracts, like proteins, enzymes, and polysaccharides, can help reduce, cap, and stabilize the NPs. Because of these things, cobalt oxide NPs made in an environmentally friendly way are more active than those made in a traditional way. Adino et al. found that cobalt oxide NPs made from green materials were better at killing bacteria than other forms of cobalt oxide NPs, even when the concentrations were low (25 mg ml−1). Phytochemicals from Phytolacca dodecandra (a plant extract) and the fact that green synthesized Co_3O_4 NPs have a higher surface area to volume ratio both help to make reactive oxygen species in biologically synthesized NPs, which then stop or kill bacteria. It is important to look at the performance metrics of green production methods for cobalt oxide (Co_3O_4) nanoparticles, such as electrical conductivity, surface area, and catalytic efficacy. These traits have a direct effect on how well the nanoparticles operate in energy and environmental settings. For example, a big surface area makes it easier for things to stick to each other in wastewater treatment. In energy storage devices, excellent conductivity makes it easier for charges to move. Nanoparticles made from plants usually have a medium-sized surface area and are very good at catalyzing reactions. However, the outcomes may not always be the same because the phytochemical content can change. Microbial production gives you fine control over particle generation and uniformity, which often leads to great catalytic properties, even though it is hard work and requires sterile conditions. Biopolymer-assisted methods, on the other hand, may cause problems with purity and repeatability. These methods increase dispersion and make surfaces that work. Green methods are good since they are safe for the environment, cost-effective, and usually work in mild conditions. But they take longer to react, the properties of nanoparticles are hard to anticipate, and it's impossible to make natural precursors the same every time. Plant-based technologies have the most potential to lower environmental impact and make things easier to scale up because they are easy to use and employ raw materials that are easy to get. Biological limits make it harder to use microbial technologies on a larger scale, even if they don't hurt the environment. Biopolymer-based methods may need more processing steps, which could make them less useful for businesses that want to use them on a large scale. A full understanding of these trade-offs is important for choosing the optimum green synthesis method, depending on the use and production needs.

12. Research Gaps & Future Perspectives

There are a number of problems that need to be solved before biogenic approaches for making cobalt oxide NPs can be used on a large scale. One of the biggest problems with enhancing synthesis procedures is making sure that the NPs that are made are all the same size, shape, and properties and can be made again. Differences in the makeup of natural extracts and microorganisms could be to blame for problems in NPs synthesis. So, it is important to have standard procedures and solid quality control systems in place. Another problem is that the processes that control the synthesis of biogenic NPs are not clear. Not much is known about how phytochemicals, reducing agents, and bioreductants work together to make NPs. More research is needed to learn more about these complex processes and figure out the best conditions for synthesis to improve the yield and properties of cobalt oxide NPs. Another concern is scalability, which is especially bad for biomedical applications on a large scale. We need to think about research in new ways, have teams of academics from diverse professions work together, and have universities, corporations, and government agencies work together to get over these problems. Cobalt oxide NPs have a lot of potential for biological use, but their biocompatibility needs to be improved. The goal of future research should be to use controlled synthesis methods to lower cytotoxicity and make interactions with biological tissues less hazardous. In the future, more research into cobalt oxide NPs could make them more useful in medicine and more effective at treating diseases by looking into their promising natural antibacterial and anticancer properties. There are many biological interactions that need more research beyond just antimicrobial and anticancer investigations. For example, drug distribution, biosensing, and protein binding are all examples. You can add unique biomolecules to cobalt oxide nanoparticles (NPs) to make personalized medicine delivery systems. Smart designs for nanocarriers and continual advances to surface changes could make it easier for medicine to get to sick cells and have fewer side effects. Creating cobalt oxide NPs with multiple functions, like diagnostics and therapy, has a lot of potential in the field of theranostic applications. Future studies should look into the prospect of combining imaging, drug delivery, and therapeutic properties into a single nanoplatform for real-time sickness monitoring and treatment. In vivo tests and extensive toxicity studies are also needed to find out how well biogenic cobalt oxide NPs work, how safe they are, and how stable they are over time. To employ these NPs safely and ethically in tissue engineering, 3D bioprinting, biosensors, organ on a chip, and other real-world settings, we need to figure out how to deal with their biocompatibility, cytotoxicity, and potential effects on the environment. If we deal with these issues, we will be able to fully harness biogenic cobalt oxide NPs and make the most of their unique properties for vital social, environmental, and technical purposes. The green synthesis of cobalt oxide (Co_3O_4) nanoparticles has come a long way, but there are still big problems that keep them from being employed more in business and industry. A big challenge is that studies don't agree on the size, shape, and surface properties of nanoparticles. One reason for this is that there are no clear production processes. Because of this inconsistency, it is not possible to accurately reproduce results or compare different synthesis techniques. Also, there are still problems with scaling up. Many eco-friendly technologies have been improved in the lab, but they might not work well when used in large-scale production because of issues like batch variability, extract instability, and a lack of easily accessible precursors. The lack of sustainability indicators and full lifecycle assessments (LCAs) is an important problem that is sometimes overlooked. These are needed to find out how nanomaterials that are green-synthesized really affect the environment and how much money they can make. Some examples of materials that could be mixed with Co_3O_4 nanoparticles in hybrid systems are graphene, polymers, and various metal oxides. This would make them more useful and allow them to be used in more areas, such as catalysis, energy storage, and cleaning up the environment. To make sure that green-synthesized cobalt oxide nanoparticles can be used in a useful and long-lasting way, it is important to solve these challenges using a variety of fields, rules, and research. Green synthesis, which is also called microbial synthesis of NMs, is a field of study that is always growing and could help us find new, well-researched, and environmentally friendly solutions to many of the world's issues. Before biogenic nanoparticles can be fully optimized and their benefits fully realized, more research needs to be done in a number of areas. Because green NM synthesis is a new field of study, not much is known about how well some natural resources, including waste materials, microorganisms, or some biopolymers, can help with this process. Biological synthesis should get greater attention and be employed more often because it has numerous advantages over physical and chemical synthesis. However, it is hard to properly use biological agents for NM synthesis since we don't know enough about how biosynthesis works. This is why biosynthesis processes can be unexpected and changeable, even when they make the same thing. Synthesis can take a lot of time and money because it can be complicated and intricate. So, it is important to use likely synthesis methods based on correct and hypothetical projected synthesis pathways. To do this, widely acknowledged theories and regulations must be created. This means that advanced and accurate nano-investigation and monitoring tools must continue to be developed to study the kinetics of the processes. It is also important to know everything about the molecules, chemicals, and living things that go into the microbial creation of NMs. The lab step is still where green synthesis works best. Because of differences between batches, laboratory-controlled biosynthesis can't currently make a lot of homogeneous NMs. Because of this, we need eco-friendly, effective, reliable, strong, and continuous flow-based synthesis methods right now. More in-depth research and techno-economic feasibility studies are needed to make and use NMs on a large scale. Also, investigations need to be done to find the best conditions for microorganisms to thrive and for NMs to be made. This is important so that microorganisms don't take too long to make NMs. Most of the NMs that are available for sale have not been made with safety and environmental sustainability as their primary priority. Also, we don't know enough about the bad effects of NMs. To make NMs less dangerous, they need to be checked and more information about how they work and move needs to be gathered. It is very important to look over the whole life cycle of the raw materials, from making them to throwing them away. More attention also needs to be paid to risk management during manufacturing, processing, storage, and discharge.

13. Conclusion

We have looked at how far plant-based, microbial, and biopolymer-assisted green manufacturing of cobalt oxide (Co_3O_4) nanoparticles has come in this study. These methods are better for the environment than traditional chemical synthesis because they consume less energy, employ fewer dangerous chemicals, and use more renewable biological resources. Plant-mediated synthesis stands out among the methods we looked at because it can manufacture nanoparticles of the right size and shape, is cheap, and is easy to utilize. Microbes and biopolymers are promising ways to do things, but they take longer and are harder to manage, especially when it comes to making surfaces functional and keeping particles stable. Green-synthesized Co_3O_4 nanoparticles have shown promising results in cleaning up the environment (for example, photocatalytic degradation and heavy metal adsorption) and in energy storage systems (for example, supercapacitors and lithium-ion batteries) because they have a large surface area, are redox-active, and are structurally stable. However, more research is needed before new ideas that come out of the lab may be used in the real world. Researchers need to standardize synthesis techniques, identify better ways to scale up production, and do extensive lifecycle assessments to show that green synthesis is indeed viable. Also, looking into how to add Co_3O_4 nanoparticles to hybrid materials and make multifunctional nanocomposites could improve their performance and make them useful in other areas. By solving these problems, green nanotechnology could make a big difference in the development of renewable energy and protecting the environment.

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