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REVIEW

Comparative Analysis and Applications of Green Synthesized Cobalt Oxide (Co_3O_4) Nanoparticles: A Systematic Review

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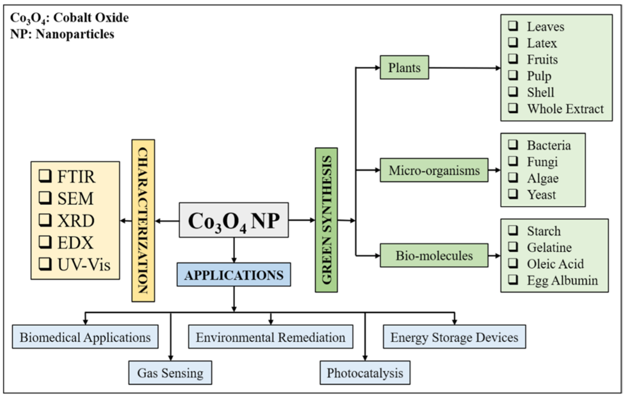
Abstract

The green synthesis method is an eco-friendly and sustainable approach to producing nanoparticles, contributing to lowering environmental impact and enhancing their compatibility for biological applications. Cobalt oxide (Co3O4) nanoparticles have recently gained significant attention due to their unique properties and diverse applications in various fields. This review presents a comprehensive comparative analysis of different green synthesis routes for Co_3O_4 nanoparticles, including plant extracts, microorganisms, and other natural sources. Various physicochemical characterization methods like X-ray diffraction, scanning electron microscopy, transmission electron microscopy, Fourier-transform infrared spectroscopy, and UV–vis spectroscopy are employed to evaluate the synthesized nanoparticles' structural, morphological, and optical properties. Also, this review examines the applications of green-manufactured Co_3O_4 nanoparticles in catalysis, sensors, energy storage devices, eco-friendly remediation, and biomedical fields. The comparative analysis highlights the advantages and limitations of different green synthesis methods regarding nanoparticle size, morphology, stability, and functional properties. Insights from this comparative analysis provide valuable guidance for optimizing green synthesis approaches and expanding the applications of Co_3O_4 nanoparticles in various domains, paving the way for sustainable and eco-friendly nanomaterial synthesis and utilization.

Graphical Abstract



Keywords Biomedical · Catalysis · Cobalt oxide (Co_3O_4) nanoparticles · Green synthesis · Physicochemical characterization · Sensors

1 Introduction

Nanoparticles and their applications are developing day by day in environmental engineering, chemical industry, medicinal field, power engineering, and information and

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Extended author information available on the last page of the article technology [1]. Nanoparticles that have different generations of size updating range from 100 to 1 nm. These nanoparticles have been synthesized by two main approaches such as top-down and bottom-up and the size range fluctuated on the concentration of the metal oxides selected. While considering the diverse methods of synthesis, green synthesis of nanoparticles provides non-toxic, eco-friendly, and safe procedures. So many metals have been used to produce nanoparticles such as Ag, Au, Fe, Co, and Rh. Production of nanoparticles with biological aids such as fungal, bacterial, and floral species needs significant molecular machinery to set sustainable development of nanotechnology [2]. Green nanotechnology deals with biological matter and gets incorporated within green chemistry. Integration of nanotechnology with green chemistry led researchers to have so many advantages such as minimum energy in the production, reduced toxicity, and an eco-friendly approach [3]. Synthesis of nanoparticles by integrating metal oxides that have transitional properties shows specific challenges in production. Among the transition series elements recently cobalt exhibited relevant attraction due to its non-toxicity in body levels and was explored as a therapeutic agent to cure different infections. Cobalt is an essential transitional metal needed to be in a nutritional diet sanitizer concentration in the food in quite a small amount. Cobalt is the major constituent element in vitamin B12 and occurs in animal protein but not in vegetables. Along with cobalt, there is also another transition element in small composition relative to cobalt. So, cobalt is taken up for the synthesis of nanoparticles. Like all other mechanisms of synthesis, here also metal oxide will undergo reduction and formulate into metal nanoparticles. Cobalt oxide is used in devices such as gas sensor selective absorbers, anode material in lithium-ion batteries, and energy storage [4]. Production of cobalt nanoparticles was through thermal decomposition, ultrasonication method, electrochemical, magnetron sputtering, and chemical reduction methods, and microorganisms, plant extract, and agricultural waste was utilized for the generation [5]. The nanocrystalline $CoAl_2O_4$ and Co_2O_3 were synthesized using the sol–gel method and classic microwave combustion methods [6]. They have also been synthesized by the polyol method, thermal decomposition, and reduction by borohydride [7], while green synthesizing nanoparticle compounds derived from plant extracts such as flavonoids, phenolic components, and tannins help in the reduction of metal oxides [8]. Recent advances show that the sustainable production of cobalt nanoparticles increases their cost-effectiveness and renewability [9]. In the transition series, the element that comes up next to cobalt in the group is rhodium and that does not get used widely for nanoparticle green synthesis. Due to its expense and availability, it was not explored more in the field of green nanotechnology. Even if the thought element is taken up for fewer studies, it has greater catalytic efficiency [10]. Because of its many uses in pharmacology and medicine, including materials, cosmetics, and tumor detection, nanotechnology has drawn a lot of attention in recent years. The burgeoning field of nanotechnology is known for its various uses and functions resulting from the size range of nanoparticles, which spans from 1 to 100 nm. Nanoparticles are thought to be advantageous fertilizers, pesticides, and plant growth agents. In the modern era, nanomaterials have become a viable alternative to conventional pest management techniques. Nanotechnology has been applied to agriculture to improve crops, diagnose plant diseases, control weeds and pests, treat soil and water problems, and improve the health and breeding of animals. The role of nanotechnology in the food business has risen [11]. One of the main areas of nanotechnology is the production of nanoparticles with different sizes, chemical compositions, and controlled mono-dispersion. Nanoparticle shape management has been a more recent necessity for the newly developed synthesis processes [12]. The reports on synthesizing rhodium nanoparticles suggest preparation from the hydrothermal and crystallization processes [13]. However, the rhodium nanoparticle is not employed by the oxide complex, then by its chloride compounds, and the studies also mention up to regulative synthesis by its control over size and shape [14]. After the formulation of the nanoparticles, it has varying physical and chemical properties that may be influenced by external and internal factors such as temperature and Ph, respectively. Different techniques like UV–VIS spectroscopy, XRD, and FTIR have been used to analyze its characterization. The nanoparticles generated from metal compounds create perspectives on their nature and way of aggregation. Collecting all the data and results obtained from the specific studies on green synthesized cobalt oxide nanoparticles will conclude with certain observations. Upon that literature will highlight to explain their application in various fields of advancements. This review aims to provide a thorough assessment of the latest advancements in the environmentally friendly manufacture and use of cobalt oxide nanoparticles. There is also discussion of the characterization procedures, green synthesis methodologies, and various applications of cobalt oxide nanoparticles. Furthermore, the mechanisms of action of cobalt oxide nanoparticles against various microbial strains, along with the obstacles and opportunities in the field going forward, will be covered. All things considered, this review work will offer insightful information on the possibilities of cobalt oxide nanoparticles, showcasing recent developments as well as upcoming chances for further study and exploration in this area.

1.1 Green Synthesis of Cobalt Nanoparticles

There is a diverse effect when synthesizing nanoparticles from chemical and physical methods. Such physical methods are achieved at high temperatures and pressure which require high energy consumption for a long time whereas chemical methods are a simpler process and carried out at low temperatures, but the use of toxic chemicals leads to diverse effects on the ecosystem or they are a threat to the ecosystem. To conquer all these problems, thus find different ways to synthesize nanoparticles that will not harm our environment or ecosystem. Plants are also biological substrates that are enhanced with various vital phytochemicals, which lessens the need for chemicals to act as reducing, capping, or stabilizing agents when metal nanoparticles are synthesized from their corresponding precursor solution (cobalt metal salts). Consequently, the term “green synthesis” refers to this technique. Green synthesis comes out as bio-absorbable, eco-friendly, and incredible, and contributes more advantages as compared to physical and chemical methods. For the environmentally friendly synthesis of nanoparticles, a variety of plants and their components—such as leaves, stems, fruits, bacteria, fungus, and other biological substances like starch—have been employed. Different plant components, biomolecules like starch, and microorganisms have all been employed to create cobalt nanoparticles [11–14]. Cobalt has been created using a variety of techniques, including chemical, biological, and physical techniques. However, both ecologically friendly and biological approaches are less polluted. Plant extracts are often made from their many parts, including flowers, bark, roots, leaves, fruit peels, fruit pulp, etc., using ethanol or filtered water as the solvent. Using this technique, cobalt nanoparticles are created. As illustrated in Fig. 1, depending on the order in which they are processed, the green approaches for creating cobalt nanoparticles from plant extracts are frequently divided into different sections.

Preparation of Extract: The first stage in making extracts is cleaning specific plant components like roots, leaves, fruit peel, pulp, etc.; drying them; and then chopping or crushing them until they are powder. To completely clean some plant parts—including dust particles, epiphytes, and related debris—distilled water was usually employed after tap water. Subsequently, the reduced plant components are boiled in a particular quantity of solution like deionized water, ethanol, etc., at a predetermined temperature. After a predefined amount of boiling time, filtering is required to separate the phytochemicals present in specific plant sections, such as phenolic acids, sugars, and their derivatives with amino, etc., in the solvents of choice [15–20].

Synthesis of Cobalt Oxide Nanoparticle: The resulting plant extracts were then mixed with cobalt metal salt precursors like cobalt nitrate, acetate, or chloride at predetermined concentrations and volumes. Phytochemicals in the extracts may function as reducing, capping, and stabilizing agents in this process, allowing the cobalt ions in the precursor solution to become cobalt oxide nanoparticles. A reaction mixture containing plant extract and cobalt metal precursor may occasionally be calcined at 300, 600, and 900 °C in a muffle furnace with air or an inert environment. To get rid of the contaminants that were left on the surface of the produced nanoparticles, the final product (cobalt nanoparticles) had to be washed once again after the calcination process [21–26]. There have been reports that the plant extract contains more active chemical components, or phytochemicals, in varying amounts that function as bio-reducers, caps, and stabilizers of the synthesized nanoparticles [27–30]. Therefore,

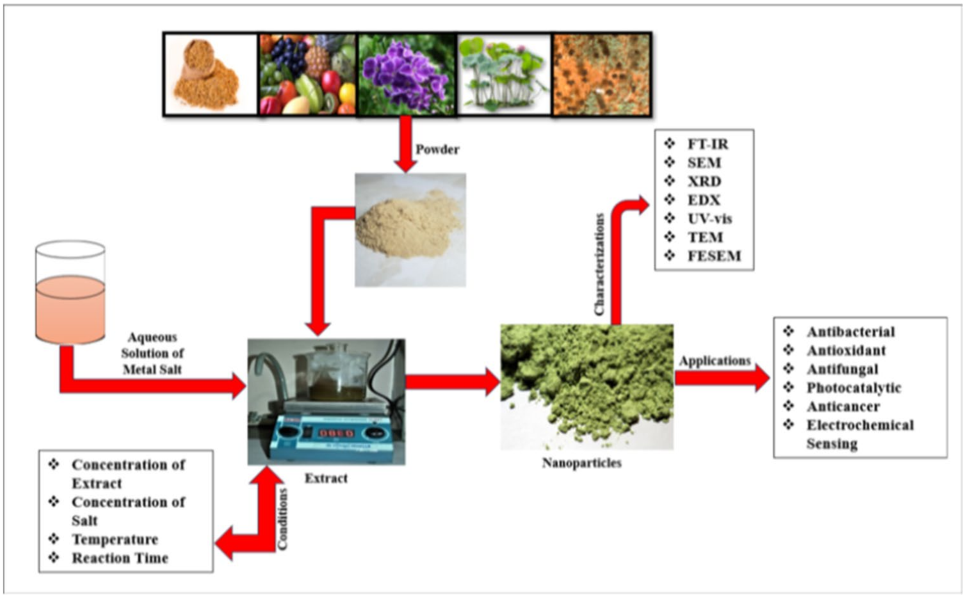


Fig. 1 Systematic illustration of cobalt oxide nanoparticles manufactured by using the plant extract method

because the number of phytochemicals and antioxidant components in plant extracts was unknown, it was hard to precisely quantify throughout the nanoparticle production process. Additionally, the kind and concentration of phytochemicals found in the selected plant parts affect the size of the generated nanoparticles. A variety of plant-based substances and their corresponding sections were taken to synthesize cobalt nanoparticles, according to current literature publications. Various strategies have been employed to comprehend function of particular phytochemicals in the production of Co NPs possessing distinct attributes. For example, Akhlaghi et al. described the production of cobalt oxide nanomaterials by reacting a cobalt precursor with an extract of fenugreek leaves and then annealing the mixture outdoors for 2 h at 500. Using a diversity of methods, together with thermogravimetric analysis, dynamic light scattering analysis, field emission scanning electron microscopy (FESEM), transmission electron microscopy (TEM), Fourier transform infrared spectroscopy (FT-IR), UV–Vis spectral analysis, X-ray diffraction, energy dispersive spectroscopy, and transmission electron microscopy (TEM), the authors described the synthesized nanoparticles. Based on information from the TEM research, the scientists stated that the synthesized nanoparticles' median particle dimension was approximately 13.2 nm. Furthermore, it was deduced from energy-dispersive X-ray (EDX), X-ray diffraction (XRD), and UV–Vis spectroscopic analysis observations that reaction solution's pH (pH ¼12) influences the purity and crystal structure of the nanoparticles in addition to being a major favor to their high yield. The authors deduced that the bioactive organic chemicals found in the fenugreek leaf extract functioned as stabilizing agents and reducing agents to transform ions of cobalt into cobalt nanoparticles [31]. Asha and colleagues synthesized cobalt oxide nanoparticles using sustainable resources, including clove and seed extracts from *Allium sativum* and *Coriandrum sativum*, respectively. Using FTIR, SEM, and EDS examination, the authors assessed the purity, superficial structure, and crystal-like characteristics of the as-prepared Co NPs [32]. In a different study, Mohammadi et al. [33] reported synthesizing Co oxide NPs with walnut green hulls due to phenolic compounds' high concentration and their physiological benefits, which include antiphrastic, antiviral, antibacterial, and fungicidal properties. High in reactivity, phenolic compounds can donate hydrogen and reduce it. In this work, plant extract (10 mL) and cobalt metal precursor were reacted on a heated plate at 70 °C to create cobalt nanoparticles. The reaction's end product was calcined for 2 h at 600 °C. During the nanoparticle production process, no stabilizing agents or surfactants were employed. As-synthesized nanoparticles were found to be dispersed (i.e., not aggregated) and to have a spherical form, with a particle size ranging from 60 to 80 nm. The authors concluded that the chosen plant extract was mostly responsible for this observation. Upon the conversion of the cobalt ion precursor into cobalt nanoparticles, the phytochemicals present in the walnut green husk extract served as stabilizing and reducing agents. However, with a saturation magnetization of 3 emu g1, the produced nanoparticles show super-paramagnetic behavior. To prevent secondary water contamination, this behavior can investigate the cobalt nanoparticles' simple separation capacity (using a magnet) when applied to contaminated water. The *Taraxacum officinale* (*T. officinale*) plant leaves are used by Rasheed et al. [34] to create cobalt nanoparticles. *T. officinale* is a flowering herbaceous plant with therapeutic properties that is rich in flavonoids (quercetin, luteolin, chrysoeriol, etc.) and phenolic acids like caffeic acid, etc. The scientists discovered that the artificial cobalt nanoparticles were closely spaced at approximately equal distances, had a spherical shape, and an average particle size of 50–100 nm by examination of TEM images. The researchers came to the conclusion that the plant extract's phytochemicals function as a capping and stabilizing agent for the individual cobalt metal particles, keeping them in the nanoscale range by dipping the magnetic induction among them. Based on the outcomes of their FTIR technique investigations, the scientists determined that polypeptides, proteins, together with phenylic acid, and acids of plant extract were accountable for the formation of Co metal ions into NPs and their constancy. Authors did observe, however, that artificially created NPs were particularly successful at quickly dissolving the dye's methyl orange and direct yellow 142 from their water solutions in the existence of $NaBH_4$. The entire conjugated chromophores' azo bond (–N—N–) cleavage in the chosen dye molecules is primary cause of the high degradation efficiency. Cobalt nanoparticles' positive surface charge, according to the authors, facilitates the adsorption of dye particles on their external, which in turn allows the particles to receive electrons from BH_4 ions in an aqueous medium. Dye's catalytic reduction was started when the recognized electrons from the BH_4 ions were directed toward dye particles. This observed behavior investigates the potential of plant extract-based synthetic cobalt nanoparticles for catalytic remediation of dye-contaminated water. Synthesis of cobalt oxide has been done by the researchers with different techniques out of which synthesis of cobalt oxide NPs by using its precursors (cobalt nitrate, cobalt chloride, cobalt acetate, and cobalt (II) sulfate) along with plant extract. Siddique et al. has done the green synthesis of cobalt oxide NPs by using the extract [35]. Simultaneously, some other researchers have also synthesized cobalt oxide NPs from its precursor salt solution by pH variation probably by increasing the pH [31]. Previous research indicates that pH plays a crucial role in the production of metal nanoparticles [36, 37]. Different plant extracts have varying pH values, necessitating further treatment before NPs can be biosynthesized [38]. Accordingly, the bio-reduction of Co^{2+} ions to colloidal NPs was investigated at various pH values. The pH of an aqueous solution containing metal ions and fenugreek leaf extract was changed by adding changed amounts of NaOH solution. We monitored reaction's development using UV–vis spectroscopy [31].

1.1.1 Green Synthesis with Plants

Due to their eco-friendliness, dependability, simplicity, and viability, plants have been employed to synthesize Co nanoparticles. Cobalt oxides have been produced using a variety of plant parts, including latex, seeds, leaves, fruits, and so forth. Nowadays, the green route synthesis from plants has increased the interest of researchers in this field [39–46]. Many works have been done to know the size of the catalyst, morphology, and shape [47–49]. Table 1 lists numerous plants that have been employed in the manufacture of cobalt oxide nanoparticles, including *Duranta repins*, *Celosia argentea*, *Mappia foetida*, *Sesamum indicum*, *Coriandrum sativum*, *Allium sativum*, *Aspalathus linearis*, and others. The corresponding plant species and their spatial characteristics are displayed in the table for the environmentally friendly production of cobalt nanoparticles.

1.1.2 Green Synthesis with Fungal Species

The fungal species have unique properties, that is, the procedure of fungi growth is easy to isolate and handle, due to the presence of biomass and proteins [50]. When the right precursors are present, fungi release bioactive substances that help with the creation of nanoparticles [51]. With the help of fungi, nanoparticles could be synthesized by two methods: intracellular and extracellular synthesis [52]. *Aspergillus nidulans*, *Aspergillus brasiliensis*, and *Saccharomyces cerevisiae* have been used to synthesize the cobalt nanoparticle as shown in Table 2.

1.1.3 Green Synthesis with *Bacteria* Species

Bacteria can also synthesize nanoparticles of various morphology and sizes. This synthesis also has some provocation as compared to other methods that are still unsolved like the formation of complex materials [53–56]. A gram + bacteria *Bacillus pasteurii* synthesized cobalt nanoparticles with an average size of 10–31 nm. Cobalt nanoparticles were synthesized using bacterial strains of *Bacillus subtilis*, *Micrococcus lylae*, *Escherichia coli*, and *Haloarcula vallismortis*. Table 3 lists a few instances of cobalt nanoparticles that were created using bacterial species.

1.2 Green Synthesis with Algal Species

Marine microorganisms called algae are often employed in the production of MNPs. Because algae generate stable nanomaterials that do not need cell maintenance, they are bio-nano-factories [62]. Proteins, polysaccharides, and phytochemicals containing $–NH_2$, –OH, and –COOH functional groups—all of which are utilized in the synthesis of MNP—are among the several bioactive compounds found in algae [63]. There are two types of algae: macroalgae and microalgae [64]. Their function group, which functions as a reducing and stabilizing agent, used green macroalgae *Grateloupia sparsa* to produce MNPs [65, 66]. Table 4 lists a few instances of cobalt oxide nanoparticles that were created using algal species.

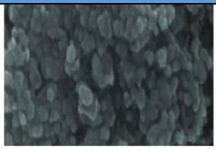
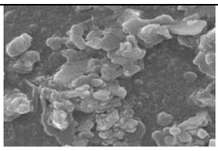
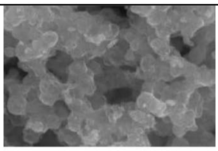
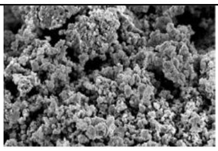
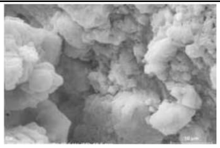
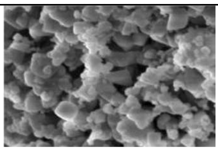
1.3 Comparison Between Green Nanoparticles from Diverse Origins

A thorough comparison of the production of cobalt oxide nanoparticles from bacteria, fungi, algae, and plants is given in the review study. It highlights the advantages and applications of each method, including the plant-based synthesis's simplicity, dependability, and environmental friendliness; the fungal species' ease of isolation and handling; the bacterial strains' ability to produce a wide range of nanoparticle shapes and sizes; and the distinct bioactive substances released by algae. Each strategy offers benefits of its own, and the best one to use will hinge on the particular requirements of application as well as the desired properties of the synthesized nanoparticles. The final decision between the approaches should be made in light of the specific characteristics required for the intended purpose. The review highlights that fungal species are easy to isolate, handle, and release bioactive compounds, whereas plant-based synthesis is straightforward, dependable, and environmentally benign. Algae have special bioactive materials, and bacterial strains can produce nanoparticles in a range of sizes and forms. The particular requirements of the application and the desired properties of the synthesized nanoparticles should guide the decision between these methods.

1.3.1 Techniques for the Characterization of Cobalt Oxide Nanoparticles (Co_2O_3)

Two major variables that are looked upon while defining NPs are their size and form. The size distribution, level of aggregation, surface charge, and surface area can all be quantified in addition to the surface chemistry to some extent [71].

Table 1 Plant extracts that are utilized to create Co_3O_4 nanoparticles

S. no	Plant	Source of plant	Phytochemical compounds	Metal salt	Morphology	Size	Ref
1.	*Citrus medica*	Leaf	Iso-limonene, flavanones, phenolics, pectin	Cobalt nitrate hexahydrate	 Spherical	39 nm	[43]
2.	*Celosia argentea*	Whole Plant	Phenols, tannis, flavonoids, glycosides, steroids	Cobalt chloride	 Spherical	27.42 nm	[44]
3.	*Polyalthia longifolia*	Leaf	Saponin, flavonoids, terpenoids, phenol	Cobalt acetate	 Quasi-spherical	40–60 nm	[45]
4.	*Duranta repins*	Leaf	Alkaloids, flavonoids, saponins, glycosides	Cobalt acetate tetrahydrate	 Spherical	23 nm	[46]
5.	*Ocium sanctum*	Leaf	Phenolics, flavonoids, terpenoids	Cobalt chloride	 Irregular spherical	30–40 nm	[47]
6.	*Walnut green hulls*	Whole Plant	Quercetin, catechin, myricetin	Cobalt nitrate	 Spherical	60–80 nm	[48]

Particle size and its distribution, and organic ligands on the particle surface may influence additional properties and probable applications of the NPs. A thorough analysis of the NPs' chemical composition and crystal structure is also conducted as a preliminary step after nanoparticle synthesis. For this purpose, there were no established procedures up until this point. The industry will be able to comply with regulations and use these materials in commercial applications with greater effect if trustworthy and accurate NP measurement methodologies are used. But there are a lot of obstacles in the way of analyzing nanomaterials: the area is multidisciplinary, there are not enough reference materials to calibrate analytical instruments,

Table 1 (continued)

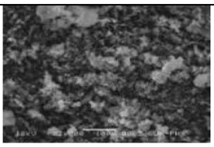
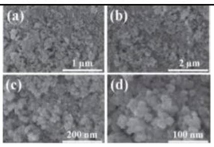
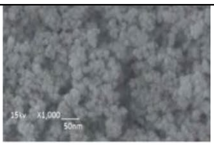
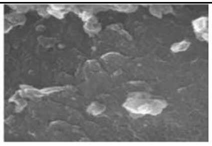
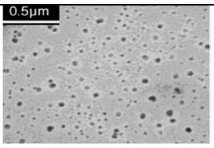
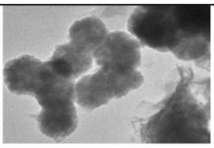
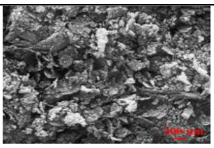
7.	*Mappia foetida*	Leaf	iridoid and flavone glycosides, terpenoids, anthraquinones	Cobalt chloride	 Spherical	5 nm	[49]
8.	*Populus ciliate*	Leaf	Phenolic compounds, flavonoids, terpenoids	Cobalt nitrate hexahydrate	 Spherical	25–35 nm	[50]
9.	*Rumex status*	Leaf	Anthraquinones, stilbenoids, carotenoids, phenolic acids	Cobalt (II) sulfate	 Spherical	52 nm	[6]
10.	*Sesamum indicum*	Leaf	Lignans, polyphenols, phytosterols	Cobalt nitrate	 Spherical	16.87 nm	[51]
11.	*Sesbania sesban*	Leaf	Flavonoids, alkaloids, steroids, phenols	Cobalt (II) nitrate hexahydrate	 Spherical	15–30 nm	[52]
12.	*Ginkgo biloba*	Leaf	Flavonoids, terpenoids, ginkgolides	Cobalt chloride hexahydrate	 Spherical core shell	_	[53]
13.	*Trigonella foenum-graecum*	Leaf	Flavonoids, alkaloids, saponins	Cobalt chloride hexahydrate	 Spherical	13.2 nm	[54]

Table 1 (continued)

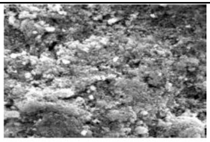
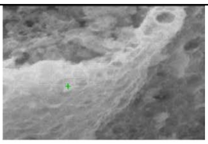
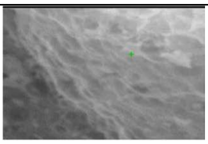
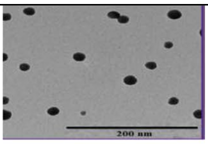
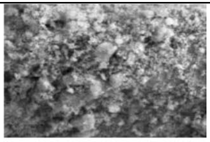
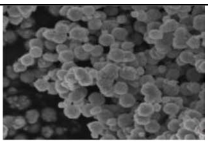
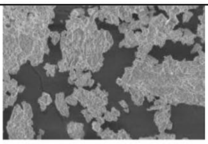
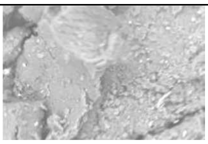
14.	*Litchi cinensis*	Leaf	Epicatechin, procyanidin (A2 and B2), saponins, stigmasterol	Cobalt acetate tetrahydrate	 Spherical	26.4 nm	[55]
15.	*Coriandrum sativum*	seeds	Gallic acid, thymol, bornyl acetate, terpene	Cobalt chloride	 Honeycomb	–	[57]
16.	*Allium sativum*	Cloves	Alliin, allicin, vinyl dithiins, quercetin	Cobalt chloride	 Fine powered	–	[58]
17.	*Calotropis procera*	Latex	Calotropin, calotoxin, steroids, stigmasterol, flavonoids	Cobalt (II) acetate	 Spherical	10 nm	[59]
18.	*Vitis rotundifolia*	Pulps	Luteolin, artemetin, phenolics, and terpenoids compounds	Cobalt chloride	 Spherical	–	[60]
19.	*Conocarpus erectus*	Leaf extract	Flavonoids, tannins	Cobalt nitrate	 Spherical	20–60 nm	[61]
20.	*Citrus limon*	Fruit	Alkaloids, flavonoids, phenols, quinines, terpenoids	Cobalt chloride hexahydrate	 Pyramid	30–40 nm	[62]
21.	*Mangifera indica*	Leaf	Mangiferin, quercetin, isoquercetin	Cobalt (II) chloride	 Cubic pentagonal	25–40 nm	[63]

Table 1 (continued)

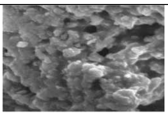
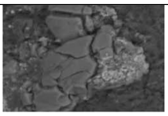
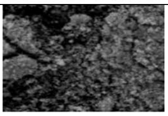
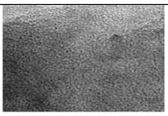
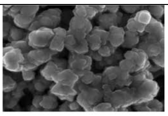
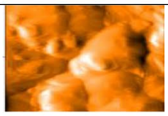
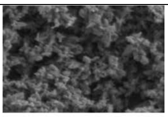
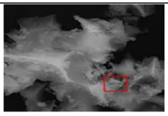
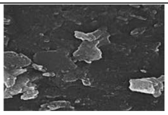
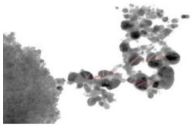
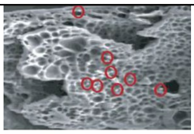
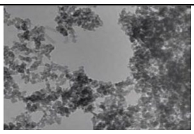
22.	*Conocarpus erectus*	Leaf	Tannin, flavonoids	Cobalt (II) chloride	 Spherical	4.9 nm	[64]
23.	*Chromolaena odorata*	Leaf	Flavonoids, terpenoids, alkaloids, saponins, tannins	Cobalt (II) nitrate hexahydrate	 Cubic and hexagonal	20–49 nm	[65]
24.	*Asparagus racemosus*	Root	Saponins and flavonoids	Cobalt acetate	 Spherical	48 nm	[66]
25.	*Moringa oleifera*	Leaves	Phenolics, flavonoids, saponins, tannins, sterols, carotenoids	Cobalt (II) chloride hexahydrate	 Crystalline cubic	20–50 nm	[67]
26.	*Sageretia thea*	Leaf	Phenolics, flavonoids, anthocyanin	Cobalt acetate	 Spherical	–	[68]
27.	*Piper nigrum*	Seeds	Piperine	Cobalt chloride	 Spherical	30–60 nm	[69]
28.	*Aloe-vera*	Latex	Steroids, anthraquinones, anthrones, phenolic compounds, flavonoids, tannins	Cobalt (II) nitrate hexahydrate	 Cubic	36 nm	[70]
29.	*Tamarindus indica*	Pulp	Phenols, glycoside, alkaloids, amino acids	Cobalt (II) nitrate	 Spongy	71 nm	[71]
30.	*Ziziphora clinopodiodes Lam*	Leaves	Chrysin, cis-caffeic acid, luteolin	Cobalt nitrate	 Spherical	28.19 nm	[72]

Table 2 Fungal species used for the synthesis of Co_3O_4 nanoparticles

S. no	Fungal species	Salt	Growing medium	Time	Morphology	Size	Ref.
1	*Aspergillus nidulans*	Cobalt (II) acetylacetonate	PDA media	3 days	 Spherical	20.29 nm	[77]
2	*Aspergillus brasiliensis*	Cobalt (II) sulfate	SDB media	72 h	 Quasi-spherical	20–27 nm	[78]
3	*Saccharomyces cerevisiae*	Cobalt nitrate	Suspension culture	24 h	 Hollow sphere	3–15 nm	[79]

sample preparation is hard, and data interpretation is tough. Moreover, there are also problems with NP characterization, namely how to evaluate concentrations in complex matrices and how to track them both in situ and online, especially in larger-scale processes. It is also essential to monitor the trash and effluent from mass production [72]. As the size of the nanoparticles produced grows, more reliable quantification techniques will be required (Table 5).

1.3.2 Applications of Cobalt Nanoparticles

Cobalt oxide nanoparticles have been found to be a multifunctional substance with typical spinal and monoclinic structures. Strong resistance to oxidation and corrosion, potential for nontoxicity, affordability, and environmental friendliness make cobalt oxide nanoparticles stand out [80]. Cobalt oxide nanoparticles have been the subject of much discussion in recent years regarding their possible applications in a variety of sectors, including heterogeneous catalysis, magnetic semiconductors, solar energy storage, electrochemical sensors, and super-capacitors [81]. Below is a summary of the information on the usage of cobalt oxide nanoparticles in photocatalytic environmental applications, including the electrochemical sensing, antibacterial qualities, anticancer activity, antioxidant activity, and water purification.

Table 3 Synthesis of nanoparticles from bacterial species

S. no	Bacterial species	Gram + or gram –	Salt	Growing median	Morphology	Size	Ref
1	*Bacillus pasteurii*	Gram +	Cobalt (II) nitrate	Yeast extract, ammonia sulfate and Tris-base	Non-specific	10–31 nm	[18]
2	*Bacillus subtilis*	Gram +	Cobalt (II) chloride	Liquid medium of Luria–Bertani broth	Hollow-rod shape	2–5 nm	[56]
3	*Brevibacterium casei*	Gram +	Cobalt (II) acetate	Zobell marine medium and minimal medium	Quasi-spherical	6 nm	[57]
4	*Micrococcus lylae*	Gram +	Cobalt (II) acetate	Bacteria and Luria–Bertani broth	Flower-like	8 nm	[58]
5	*Escherichia coli*	Gram –	Cobalt chloride	Luria–Bertani broth	Rod shape	473–54 nm	[59]
6	*Paracoccus sp.*	Gram –	Cobalt chloride	Luria–Bertani broth	Biconcave shape	NA	[60]
7	*Haloarcula vallismortis*	Gram –	Cobalt chloride	Yeast extract, tri-sodium citrate, and magnesium chloride complex medium	Globular	NA	[61]

Photocatalytic Degradation of Dyes: Chemicals known as dyes, which have certain functional groups like chromophores, auxochromes, conjugated systems, etc., are widely employed as colorants on a variety of substrates, including paper, leather, and cloth, to create eye-catching products. But in the process of coloring, a significant amount of dye-tainted colored wastewater was produced. This poses a great risk to all living creatures, especially individuals and animals, and to the environment [82]. In the process of dying substance, the dye waste gets washed away in the water and makes the water injurious for animals as well as humans [83]. Cobalt nanoparticles can be used to solve these issues; cobalt NPs help to remedy contaminated water because of their high photocatalytic and adsorptive activity. Under appropriate light irradiation, the photocatalytic function of nanoparticles of cobalt for the decomposition of dyes like methyl red, malachite green, etc., was examined [84]. The photocatalytic activity of cobalt oxide nanoparticles made via green synthesis with aloe vera latex as fuel. The study investigates the synthetic cobalt oxide nanoparticle's ability to degrade dye photocatalytically, focusing on the AR-88 dye under UV light irradiation. Based on the study's findings, the cobalt oxide nanoparticles were able to degrade the AR-88 dye to a maximum of 97.6% after being exposed to UV light for 135 min. The study also assesses the CO photocatalyst's stability and recycling capabilities, demonstrating its efficacy in the photocatalytic destruction of dyes. Because of their photocatalytic activity, Table 6 illustrates how cobalt oxide nanoparticles may be applied in environmental cleanup and water treatment [58]. Accordingly, it can be inferred from the above-mentioned data that cobalt nanoparticles with multifunctional surfaces are very helpful in the breakdown of dyes from contaminated water due to their photocatalytic property.

Table 4 Synthesis of nanoparticles from algal species

S. no	Algal species	Metal salt	Extract	Morphology	Size	Ref
1	*S. platensis*	Cobalt (II) chloride hexahydrate	Methanolic	Octahedral	26.1 nm	[67]
2	*C. vulgaris*	Cobalt (II) chloride hexahydrate	Methanolic	Spherical	16.4 nm	[67]
3	*H. pluvialis*	Cobalt (II) chloride hexahydrate	Methanolic	Spherical	18.4 nm	[67]
4	*Grateloupia sparsa*	Cobalt (II) nitrate hexahydrate	Double-distilled water (DDI)	Spherical	8.03 nm	[68]
5	*Grateloupia sparsa*	Cobalt (II) nitrate hexahydrate	DDI	Inhomogeneous spheres	28.8 to 7.6 nm	[69]
6	*Red Algae*	Cobalt (II) nitrate hexahydrate	Deionized water	Spherical	29.07 nm	[70]

Sonkusare et al. [58] have reported comparable observations utilizing CoO-NPs for the photocatalytic degradation of methyl red, bromophenol blue, erichrome black-T, and malachite green when exposed to visible light. Photocatalytic activity was assessed using UV–visible dye spectra as a function of time before and after treatment with Co oxide NPs and (LC–MS) analytical techniques. With a 50 mg dosage of nanoparticles, authors saw excellent and quick photocatalytic destruction of specific dye molecules after 40-min exposure to visible light. Significant photocatalytic efficacy was primarily attributed to the electrons (e) hole (hþ) phenomena, the structure of metal nanoparticles, and an appropriate band gap energy among the valence band and the conduction band of Co oxide NPs. The valence band electrons were stimulated by visible light irradiation and moved to the conduction band, where they formed the corresponding holes (h). As a result, e-hξ pairs are bound together with dye molecules by oxygen and water molecules on the vigorous surface of Co oxide NPs. As a result, powerful dye-oxidizing agents known as superoxide radical anion and active OH radicals were created. The colored aquatic dye solution was then reacted with by the potent oxidizing radicals that were created, oxidizing the dyes and rendering them colorless. In addition to the phenomenon of e-hÍ pairs, many characteristics like as specific surface area, meso-porosity, and surface shape were found to be responsible for the CoO-NPs' enhanced ability to destroy dye molecules through photocatalysis. Additionally, the authors used LC–MS analysis to determine the dye photodegradation product resulting from the reaction with cobalt nanoparticles. Within 45 min of the response, they saw 100% degradation, and they saw degradation products as soon as 15 min. A different recent work by Samuel et al. [81] assessed the photocatalytic activity of cobalt oxide NPs through degrading the cationic dye "acid blue-74" from aqueous solution under UV light irradiation. In this study, *Vitis rotundifolia* extract was used by authors to create cobalt oxide NPs. When related to the early pH of the solution in the acidic range, authors found that synthesized nanoparticles were formed like a rhombus and showed strong photochemical degradation competence for acid blue-74 dye at a pH scale increase of 10. The behavior could perhaps result from the surface of the nanoparticles exhibiting a distinct charge when the initial pH of the reaction solution increases, according to the authors' conclusions. The strong

Table 5 Various analytical techniques with their functions in the investigation of nanoparticles

S. no	Characterization technique	Entity characterized	Detailed information	Ref
1	X-ray diffraction (XRD)	Size, elemental chemical composition, crystal structure	Utilized to characterize nanopowders in every size range, give helpful details and assist in establishing a relationship between microscopic observations and the bulk sample	[73]
2	Fourier transform infrared spectroscopy (FT-IR)	Ligand binding, composition, density, arrangement	To research metal nanoparticles' surface chemistry, used to identify polymeric, inorganic, and organic compounds by scanning samples with infrared light, utilized to locate functional groupings within the content	[74]
3	Scanning electron microscopy (SEM)	Size (structural properties), size distribution, agglomeration state, NP dispersion in matrices and NP detection	Obtain a three-dimensional look by observing how the electron beam interacts with the sample's surface	[75]
4	Transmission electron microscopy (TEM)	Size (structural properties), Shape, growth kinetics, agglomeration state, single particles properties, structural defects	Obtain higher quality images than with a light microscope, utilized to investigate the presence and structure of NPs	[76]
5	UV–visible	Size (structural properties), concentration, agglomeration State,	Employed for the materials' optical analysis and to determine the NPs' production	[77]
6	Field emission scanning electron microscope (FESEM)	Size (structural properties), Shape, crystal structure, single particles properties, structural defects	Utilized to obtain a picture of the material's microstructure	[78]
7	Centrifugation	Separation	To take the created NPs out of the reaction mixture	[77]
8	Energy dispersive X-ray spectrometry (EDS)	Elemental chemical composition	Used to determine a sample's elemental composition	[79]

Table 6 Degradation of dyes

Degradation at 40 min (%)		
Dye	Without catalyst	Presence of cobalt NPs
Methyl red	33.9	95.3
Eri-chrome black-T	22.6	94.3
Bromophenol blue	26.7	89.8
Malachite green	1.81	93.7

Sonkusare V.N., Chaudhary R.G., Bhusari G.S., Mondal A., Potbhare A.K., Mishra R.K., Juneja H.D., Abdala A.A., "Mesoporous Octahedron-Shaped Tricobalt Tetroxide Nanoparticles for Photocatalytic degradation of toxic dyes", ACS Omega, 2020,5,14,7823–7835

photochemical degradation efficiency in the occurrence of UV light was attributed by scientists to the formation of electron–hole pairs on the surface of NPs and charge transfer between dye molecules and the NP catalyst. Furthermore, by doping other metallic nanoparticles at the right concentration, cobalt oxides can improve their photodegradation efficiency in addition to their photocatalytic efficacy. By using *Salvadora persica* bark extract, Hanidian et al., [85] for example, created cobalt-doped. Trimethylamine, sulfur compounds, sodium bicarbonate, isothiocyanide compounds, fluorine, and fluoride are all substantially concentrated in *Salvadora persica* wood. To assess the Co–CeO_2 NPs' ability to degrade an aqueous solution of "acid orange 7," the impact of cobalt doping on their photocatalytic activity was assessed. Authors found that the 7% cobalt doping greatly improved the green synthesized nanoparticles' photocatalytic efficiency. It was found that the band gap and photocatalyst-specific surface area affect the photocatalytic behavior. The authors also observed that when cerium nanoparticles are added to 7% Co, the band gap narrows, and the surface area of the resultant nanomaterial increases.

Antibacterial Activity: A chemical, substance, or material's antibacterial activity is directly related to its capacity to eradicate germs or inhibit their growth without posing a significant risk to neighboring tissues. Thus, antimicrobial compounds can be categorized as bacteriostatic or bactericidal based on their characteristics [86]. The antibacterial properties of metallic and metal oxide NPs, including copper, silver, zinc, and magnesium oxides, have been demonstrated. They can be used in a range of antibacterial applications because of these qualities as well as their smaller particle sizes, distinct surface morphologies, and biocompatibility [87]. Nanoparticles have a nanosize with a higher surface area due to which they show antibacterial activities. CoNPs do not damage the surrounding tissue; instead, they can eliminate germs and slow their rate of growth. Additionally, CoNPs exhibit antibacterial efficacy against mutant *Streptococcus*, *T. coli*, and *Pseudomonas aeruginosa* [88].

CoNPs show inhibition against the bacterial pathogen. Due to their biocompatible smaller particle sizes, nature, and novel surface structure, various metallic and metal oxide NPs, such as ZnO, have been claimed to be anti-bacterial. Similar to how gram-positive (G+) and gram-negative (G−) bacterial strains were assessed about cobalt nanoparticles made from plant extract. According to the results of these investigations, every synthetic cobalt nanoparticle demonstrated a strong antimicrobial response, albeit with varying zones of inhibition about the changes in bacterial strains. Consequently, it is evident from the literature review that using plant extracts to create environmentally friendly cobalt oxide nanoparticles is very successful overall. This is because the extracts have strong antimicrobial activity in contrast to a variety of gram-positive and gram-negative bacterial strains in addition to photocatalytic activity and electrochemical sensing. To create Co oxide NPs from the cobalt precursor, Khalil et al. [89] use the *Sageretia thea* extract as a chelating agent. The produced cobalt nanoparticles' antibacterial activity was assessed against three strains of bacteria, three of which were g-negative (*Klebsiella pneumonia*, *Escherichia coli*, and *Pseudomonas aeruginosa*) and three of which were g-positive (*Staphylococcus epidermis*, *Staphylococcus aureus*, and *Bacillus subtilis*). The scientists discovered that cobalt nanoparticles that were synthesized and had particle size of 20.03 nm (based on XRD measurement) had a higher zone of inhibition and good antibacterial activity. According to the author's observations, the dose of synthesized nanoparticles boosts the antibacterial response. The author concludes that the dose of the nanoparticles affected their antibacterial activity. Additionally, it was shown that while the synthesized nanoparticles showed a high antibacterial response, their zone of inhibition was smaller than that of the control antibiotic (gentamycin) disc. Furthermore, as per the literature, the synthesis of CoO-NPs has been carried out using extracts from several other plants, including *Sesbania sesban*, *Phoenix dactylifera*, and *Celosia argentea* [90–92]. The antimicrobial efficacy of these extracts has been investigated against a range of gram-positive and gram-negative bacterial strains. According to the findings of these investigations, every synthetic cobalt nanoparticle demonstrated a strong antimicrobial response. There may have been variations in the zone of inhibition, either higher or lower, depending on the strains of bacteria. Overall, then, it is evident from a review of the literature that using plant extracts to create environmentally friendly CoO-NPs is very successful. These CoO-NPs have strong antimicrobial activity against a variety of gram-positive and gram-negative bacterial strains in addition to photocatalytic activity and electrochemical sensing.

Anticancer Activity: The green synthesis of CoNPs possesses the activity opposed to the cancer cell due to the presence of more surface area and magnetic properties. The CoNPs help in the treatment of the cancer cell [93, 94]. CoNPs show anticancer activity against the human colorectal adenocarcinoma cell line (HT-29) and SW-620. The CoNPs synthesized from *Euphorbia tirucalli* also show anticancer activity against breast cells. Numerous research has demonstrated that cobalt nanoparticles may be produced using environmentally friendly techniques and have anticancer properties. When making cobalt nanoparticles, we harvest the leaf of *Rhamnus virgata*. The outcome revealed the cobalt nanoparticles' anticancer toxicity. With an IC50 value of 150.8 µg/ml, CL-cobalt oxide showed anticancer efficacy toward MDA-MB-468 cancer cell lines [95]. The green production of cobalt oxide nanoparticles (CoONPs) utilizing pomegranate (*Punica granatum L.*) seed oil is discussed by Pranjali Bajrang et al. along with its possible uses in antibacterial and anticancer properties. Analysis of the active metabolites in the seed oil and in vitro cytotoxicity assessment using malignant and non-cancerous cell lines are included in the study. According to the findings, the green synthetic CoONPs have a high cytotoxicity against malignant cell lines, suggesting that they could be used as an anticancer treatment. The study also looks at pomegranate seed oil's possible uses in medicine and business, in addition to its culinary use [96]. Co_3O_4NPs showed a strong anticancer potential (IC50 = 41.4 lg/ml) as reported by Ajarem et al.

Figure 2 demonstrates an 80% estimated mortality at 500 lg/ml. Our findings demonstrated that CO_3O_4NPs that interact with cells produce ROS [70]. The production of ROS can trigger oxidative stress in cells, which damages DNA and causes cell death. The cell barrier and its function are also destroyed by the tiny nanoparticles' solubility and ease of penetration across the membrane. The intracellular pH 4.5

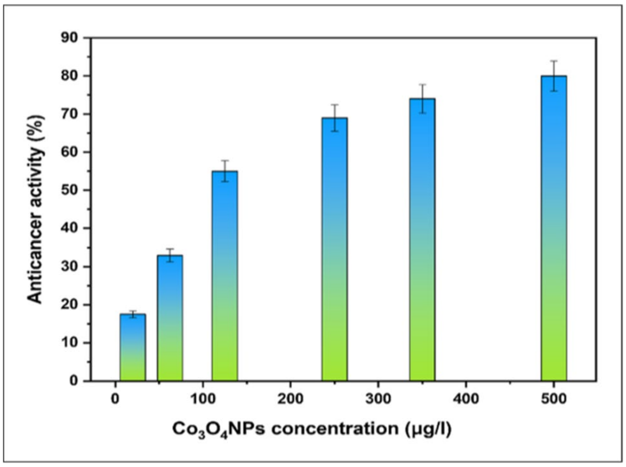


Fig. 2 The in-vitro anticancer activity of Co_3O_4NPs in the hepatic cancer cell line HepG2 [70]. {J.S. Ajarem, S.N. Maodaa, A.A. Allam, M.M. Taher, M. Khalaf (2021). Benign synthesis of cobalt oxide nanoparticles containing red algae extract: Antioxidant, antimicrobial, anticancer, and anticoagulant activity. *Journal of Cluster Science*. https://doi.org/10.1007/s10876-021-02004-9}

acid medium disintegrated the CO_3O_4NPs once they entered the cells, and the metal ions that resulted from their formation generated the membrane's holes. Furthermore, by suppressing cancer cells, CO_3O_4NPs showed strong anticancer potential.

Electrochemical Sensing Application of Cobalt Oxide Nanoparticle: Excellent electrical conductivity, excellent electroactive sites, and stability characterize the cobalt oxide nanoparticles that are created using plant extracts. They are helpful in a variety of electrochemical sensing applications due to their wide linearity spectrum, selection, low detection limit, and consistent performances [97]. For example, a study by Sharma et al. described the use of *Nigella sativa* seed aqueous extract in the bio-reduction of cobalt nitrate to create cobalt oxide nanoparticles. In this experiment, a 0.02 M water-based solution of cobalt nitrate was mixed with 15 ml of *Nigella sativa* water-soluble extract [98]. To produce precipitates, the resultant mixture was raised to 85 °C for 30 min while getting constantly agitated. As a result, the precipitate was produced, cleaned with ethanol and distilled water, and then dried in an oven for 10 h at 80 °C. The produced nanoparticles were further altered with the ionic polymer Nafion and then added to an electrode made of glassy carbon for hydrocortisone electrochemical detection using differential pulse and cyclic voltammetry. The synthesized cobalt oxide nanoparticles were found to have a spherical morphology with an average diameter of 8.7 nm. Their size ranged from 2 to 18 nm, according to TEM investigation. The functional surface area of the glassy carbon electrode was found to be greatly increased by the Nafion-modified cobalt oxide nanoparticles, according to the authors. As a result, the sensor demonstrated a low limit of detection for hydrocortisone as high recovery (97.7%–102.5%) in samples of pharmaceutical injection and blood serum. According to scientists, Nafion bonded with the as-synthesized cobalt oxide nanoparticles on the glassy carbon electrode surface through its oxygen atoms, forming a hybrid system known as Naf-CoO/GCE. When an electric current is supplied, this created hybrid system reacts strongly with the oxi-red ionizable protons (04) of hydrocortisone. Consequently, because there were more oxi-red ionizable protons present, electrical conductance increased as hydrocortisone concentration increased. Memon et al. have described the combination of cobalt oxide nanoparticles utilizing leaf extract of *Duranta repens* L., also referred to as golden dew or sky flower, in a work that is similar to this one [99]. The manufactured cobalt oxide nanoparticles—crystalline size—was assessed using the Debye Scherer equation based on XRD analysis pattern results. To achieve a homogenous dispersion, cobalt oxide nanoparticles with 23 nm were combined with 0.1% Nafion solution and sonicated for approximately 20 min. The resultant uniform dispersion was applied to the glassy carbon electrode surface by drop-casting technique and allowed to settle at ambient temperature. The tramadol drug was detected electrochemically in pharmaceutical samples using a surface-modified glassy carbon electrode. The scientists noted that with a linear range of 0.5–45 µM and a detection limit of 0.001 µM, the modified electrode surface was very successful at determining tramadol. According to the authors, the combination of cobalt oxide nanoparticles and Nafion on the electrode surface provides a highly active surface area, good electrochemical phases, and a particular interaction ability. Drawing from their findings, the authors concluded that a cost-effective and high-quality electrochemical method for detecting tramadol in pharmacological samples at very low detection limits can be achieved by synthesizing cobalt oxide nanoparticles using plant extract and applying them to the surface of sensing electrodes in combination with Nafion.

Antioxidant Activity: When Ajarem et al. generated green's Co3O4NPs, their capacity to scavenge free radicals was evaluated using a radical scavenging experiment without DPPH [71] According to these results, which included four distinct Co_3O_4NP concentrations, the activity rose as the concentration of Co_3O_4NPs increased (Fig. 3). At 500 mg/ml, DPPH showed its maximal radical scavenging of 78.1%. The highest amount of DPPH scavenging was seen at 500 mg/ml (78.1%), while lowest amount was found at 62.5 mg/ml. Despite the fact that the lowest recorded DPPH scavenging was at 62.5 mg/ml, Co_3O_4 nanoparticles are supposed to work as electron donors, interrelating with free radicals to convert them into more stable molecules that can interrupt the radical chain reaction.

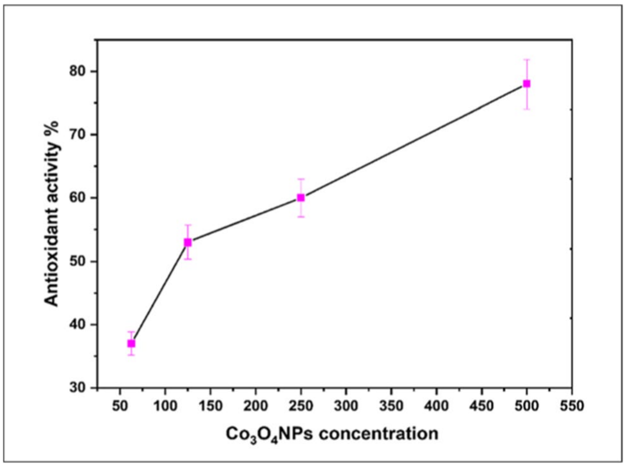


Fig. 3 The scavenging action of Co_3O_4NPs on DPPH radicals [71]. {J.S. Ajarem, S.N. Maodaa, A.A. Allam, M.M. Taher, M. Khalaf (2021). Benign synthesis of cobalt oxide nanoparticles containing red algae extract: Antioxidant, antimicrobial, anticancer, and anticoagulant activity. *Journal of Cluster Science*. https://doi.org/10.1007/s10876-021-02004-9}

The antioxidant activity of flavonoid and polyphenolic elements found in *P. guajava* leaf extracts shields cells from oxidative stress brought on by free radicals. Engaging in free radical scavenging activities is essential to preventing the detrimental effects of cancer and other disorders. The DPPH assay was typically used to test plant extracts' antioxidant capabilities. Antioxidants are known to have an impact on DPPH because of their capacity to donate hydrogen [100]. Depending on the concentration, the chemicals removed into a violet DPPH solution are reduced to a yellow color. Figure 4 [101] shows the *P. guajava* Co_3O_4 nanoparticle capacity to scavenge free radicals (DPPH). At a concentration of 50 µg/ml of *P. guajava* Co_3O_4 nanoparticles, the DDPH assays showed considerable DPPH activity. Comparing the 50 µg/ml concentration to the conventional ascorbic acid, however, 67% of the activity was displayed. Because they have a high capacity to donate hydrogen to scavenge DPPH radicals, *P. guajava* leaf extracts with high total phenolic and flavonoid content demonstrated substantial DPPH radical-scavenging activity. The findings of the present investigation were in line with those published by Jahani et al. [102]. The tendency of phenolic and flavonoid components to donate electrons to scavenge DPPH radicals increases with their content, which explains why there is a significant correlation between the extracts' phenolic and flavonoid content and their ability to scavenge DPPH radicals. The good oxidative properties of *P. guajava* Co3O4 NPs may help to explain it. Furthermore, flavonoids, phenolic substances, and secondary metabolites are present in *P. guajava* leaf extracts. The *P. guajava* Co_3O_4 NPs that are synthetic exhibit strong antioxidant capabilities.

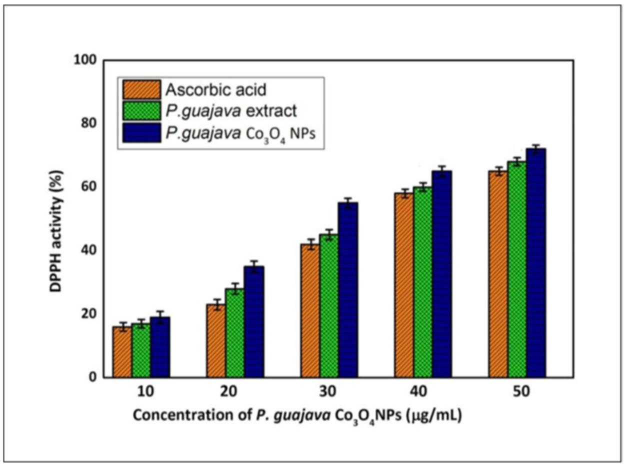


Fig. 4 Using the DPPH test, *Psidium guajava* Co_3O_4 NPs demonstrated antioxidant activity. The findings are shown as mean ± SD, measured in triplicate [[101]]. {Rajakumar. G, Vaishnavi. R, Sonalika. S, Mydhili. G, Sulthana. S, Kaliaperumal. R, V. Devi. R, et al. (2022). Green synthesis and characterization of cobalt oxide nanoparticles using Psidium guajava leaves extracts and their photocatalytic and biological activities. Molecules. 2022; 27:5646. https://doi.org/10.3390/molecules27175646}

2 Conclusion

The present work summarizes that green synthesis methods are very advantageous over conventional chemical routes in terms of eco-friendliness and cost-effectiveness ultimately reducing environmental impact. The comparative analysis revealed variations in the synthesis parameters, morphologies, sizes, and properties of Co_3O_4 nanoparticles obtained through different green synthesis approaches. These variations highlight the importance of selecting appropriate green synthesis methods for the specific application requirements, whether it is in energy storage, catalysis, sensing, biomedical applications, or environmental remediation. However, the widespread applications of green-synthesized Co_3O_4 nanoparticles highlight their immense potential in addressing global challenges, ranging from energy storage for renewable energy systems to pollutant degradation in water and air. Some other remarkable properties are high surface area, excellent catalytic activity, and biocompatibility which further enhance their utility across various fields. Apart from promising advancements, several challenges need to be addressed like scalability, reproducibility, stability, and toxicity concerns associated with green synthesis approaches and nanoparticle applications. Also, research efforts should focus on overcoming these challenges through innovative synthesis strategies, thorough characterization techniques, and rigorous toxicity assessments to facilitate the translation of green-synthesized Co_3O_4 nanoparticles from laboratory-scale studies to practical applications. Overall, this systematic review underscores the significance of green synthesis methods in advancing the synthesis and applications of Co_3O_4 nanoparticles.

3 Future Aspects and Challenges

- The requirement to enhance the synthesis process in order to manufacture larger and higher-yield products.
- When producing on a huge scale, environmentally friendly nanoparticles, it is also necessary to identify the precise phytochemicals from plant extracts that serve as reducing, capping, and stabilizing agents and to quantify their component parts.
- Concerns like toxicity, repeatability, scalability, and stability related to green synthesis techniques and nanoparticle applications are also challenges.

- To enable the transition of green-synthesized Co_3O_4 nanoparticles from laboratory-scale studies to real-world applications, research endeavors ought to concentrate on surmounting these obstacles via inventive synthesis methodologies, comprehensive characterization procedures, and exacting toxicity evaluations.

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Declarations

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