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Green synthesis of cobalt oxide nanoparticles using plant extracts: A comprehensive review of synthesis, characterization, and applications

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Abstract

Cobalt nanoparticles (CoONPs) have start out being a popular research subject. Previously manufactured using traditional physical and chemical techniques, these nanoparticles frequently involve harmful chemicals, high energy consumption, and environmental hazards. For this reason, worldwide efforts promote sustainable and environmentally conscious production processes. In this situation, green part extracts gotten from plant are gaining appeal as a sensible alternative. This technique is popular since it has many benefits: free, biocompatible, easy to scale up, and most importantly it eliminates the necessity of extra stabilizer during nanoparticulation. Phenols, alkaloids, terpenoids, and tannins phytocompounds abundant naturally are crucial ingredients. The secret rests in their natural constitution. These two-in-large-dose phytochemicals reducing agent and sealing agent are effective in converting cobalt precursors into stable and practical nanoparticles. Utilizing extracts from various plant components roots, bark, and leaves, this thorough study addresses recent developments and findings in the synthesis of cobalt oxide nanoparticles. Furthermore, researching their traits is vital for studying nanoparticles including X-ray diffraction (XRD) and transmission electron microscopy (TEM), SEM, FTIR, EDS, UV-Vis spectroscopy etc. with great equipment for establishing their form, size, and architecture. We also highlight the great advantages of cobalt nanoparticles created from cobalt green in several applications. By investigating their part in antimicrobial activity, chemical sensitivity, water pollution treatment, and photocatalytic environmental cleanup, this study hopes to provide a vivid picture.

Keywords: *Green synthesis, Cobalt oxide nanoparticles (CoONPs), Plant extract, Biogenic synthesis, Nanomaterials, Phytochemicals.*

Introduction

The synthesis of nanomaterials has been a cornerstone of modern science and technology, driving innovations across medicine, energy, and electronics. Traditionally, these materials were produced using conventional physical and chemical methods, which, while effective, often rely on harsh, energy-intensive processes. Techniques such as hydrothermal synthesis, sol-gel, and co-precipitation commonly utilize toxic precursors and reducing agents, leading to significant environmental burdens and safety risks [1-3]. The high temperatures and pressures required for these methods also make them expensive and difficult to scale up sustainably. This has ignited a global imperative to transition toward greener, more benign synthesis routes that align with the principles of sustainable chemistry [4].

The limitations of conventional methods have paved the way for green synthesis, an approach that leverages biological entities as non-toxic and cost-effective nano-factories. This paradigm shift offers a promising solution by harnessing the power of nature to fabricate nanomaterials. Among various biological resources—including bacteria, fungi, and algae—the use of plant extracts has emerged as a particularly attractive and scalable method [5]. Plants are abundant, renewable, and contain a rich array of phytochemicals such as polyphenols, flavonoids, terpenoids, and alkaloids. These compounds serve a dual purpose: they act as powerful reducing agents to convert metal ions into nanoparticles and as effective capping agents to stabilize the newly formed particles and prevent unwanted aggregation [6]. The one-pot, low-temperature nature of this synthesis route makes it exceptionally simple and economically viable.

Within the vast landscape of nanomaterials, cobalt oxide nanoparticles (Co_3O_4 NPs) have garnered immense scientific and industrial interest. As a p-type semiconductor with a unique spinel structure, Co_3O_4exhibits a rare combination of properties, including excellent electrochemical performance, high catalytic activity, and intrinsic magnetic behaviour [7]. These attributes make Co_3O_4 NPs highly versatile, with applications spanning a wide range of critical fields. In energy storage, they are being explored for use in high-performance lithium-ion batteries and supercapacitors due to their high theoretical capacity and structural stability [8]. In catalysis, they are utilized for environmental remediation, such as the degradation of organic dyes and pollutants via photocatalysis [9], their antibacterial and anticancer properties make them valuable in biomedical applications [10].

Recent studies have highlighted the remarkable versatility of plant-mediated synthesis for producing Co_3O_4 NPs with tailored properties. Researchers have successfully used a diverse range of plant sources, including *Hyphaene thebaica* fruit extract [12], *Clitoria ternatea* flower extract [11] and *Annona muricata* leaf extract [13]. These studies demonstrate that the choice of plant extract significantly influences the final morphology, size, and crystallinity of the nanoparticles. The controlled synthesis achieved through green methods allows for fine-tuning the properties of Co_3O_4 NPs to optimize their performance for specific applications.

Due to its exceptional characteristics and widespread use in a variety of sectors, including photocatalysis, antimicrobial entertainment, and chemical sensitivity, cobalt nanoparticles are now a topic of study. In the past, these nanoparticles were created using conventional physical and chemical techniques, but these methods often involve harmful chemicals, high energy usage, and environmental dangers. Consequently, there are worldwide initiatives to encourage environmentally beneficial and sustainable manufacturing techniques. Plant extracts-based green components are becoming increasingly popular as a viable alternative in this scenario. Due to its numerous advantages, this method is well-liked: free, biocompatible, simple to scale up, and most importantly, it does not require the addition of stabilizing chemicals during the creation of nanoparticles. Plant extracts are naturally composed and provide a wealth of phytochemicals, including phenols, alkaloids, terpenoids, and tannins. In high concentrations, they perform two functions: they act as a reducing agent and a sealing agent. These phytochemicals successfully transform cobalt precursors into stable and practical nanoparticles.

Plant-mediatedSynthesis of Cobalt Oxide Nanoparticles

Because the manufacture of Co_3O_4 NPs using plants is quick, clean, environmentally friendly, non-pathogenic, and low, it has attracted curious interest. protocol, which offers a one-pot method for synthesis. Combining biomolecules such as tannins, proteins, amino acids, enzymes, polysaccharides, sugars, alkaloids, phenols, saponins, terpenoids, and others reduces and stabilizes Co_3O_4 NPs. vitamins that are naturally found in the plant-accommodating. The process for making NPs includes gathering the desired plant portion (leaf, latex, flower, root, seed, peel, and fruit) from the plant. Sites should be cleaned twice or three times with plain water to get rid of the epiphytes and any surrounding debris. The sterile distilled water is then used to rinse them, if there are any undesirable elements. These fresh and clean plant components are either ground to a fine powder using a household blender or dried before being utilized to produce extract. About 10 grams of fresh or dried powder is boiled with 100 millilitres of deionized distilled water to make the plant broth. After that, the extract is carefully filtered until there is no insoluble matter in the broth. The reduction of the cobalt ion to produce Co_3O_4 NPs is followed by the addition of the cobalt metal salts precursor into the plant broth. The phytochemical is simply extracted and combined with cobalt salt solution; there is no need to introduce any outside chemicals, such as a reducing agent or stabilizers. Their presence in extract serves as a stabilizing factor in the production of Co_3O_4 NPs. The comprehensive procedure for the green synthesis of Co_3O_4 NPs by the extract from *Aspalathus linearis*leavesis described [14]. The produced Co_3O_4 NPs solution is then centrifuged to separate the NPs, and the resulting solution is well rinsed with appropriate solvents and it's followed by calcination process at 400-500°C. The resulting NPs are ground into a fine powder, which is then gathered for additional analysis [15]. Additionally, to the previously mentioned, different plants and their parts utilised for the biosynthesis of cobalt and cobalt oxide nanoparticles with their morphology, size and applications are presented in table no. 1

Table 1: The plant-mediated Biogenic Synthesis of Cobalt Oxide Nanoparticles

Plant name	Parts used in Synthesis	Precursors salt	Size	Shape of NPs obtained	Applications	Ref.
Citrus tangerina	Leaves	$Co(NO_3)_2{\cdot}6H_2O$	90–130 nm	Octahedral	Antimicrobial, antioxidant, and anti-inflammatory	13
Juglans regia	Bark	CoCl2·6H2O	—	Spherical	Environmental, antibacterial, and cytotoxic potential	14
Blumea lacera	Leaves	$CoCl_2{\cdot}7H_2O$	5–10 nm	Spherical	Antimicrobial	15
Punica granatum L.	Seed oil	$CoCl_2{\cdot}6H_2O$	129.6 nm	Spheroidal	Antimicrobial and anticancer	16
Cocos nucifera	Fruit	$Co(NO_3)_2{\cdot}6H_2O$	18.44 nm	—	Photocatalytic and antibacterial	17
Aloe vera	stem	$Co(NO_3)_2{\cdot}6H_2O$	—	Rod shape	Oxygen evolution reaction	18
Croton Macrostachyus	Leaves	$Co(NO_3)_2{\cdot}6H_2O$	12.75 nm	Irregular Spherical	Antibacterial activity	19
Carboxymethyl cellulose	Sugarcane molasses	$Co(NO_3)_2{\cdot}6H_2O$	27.2 nm	Spherical	Biological activities	20
Conocarpus erectus	Leaves	—	20–60 nm	Spherical	—	21
Ziziphus oenopolia	Leaves	$CoCl_2{\cdot}6H_2O$	27 nm	Irregular	Antimicrobial	22
Apium graveolens	Leaves	$Co(NO_3)_2{\cdot}6H_2O$	21–55 nm	Irregular	Antibacterial activity	23
Camellia sinensis	Stalks	$Co(NO_3)_2{\cdot}6H_2O$	21–72 nm	Irregular	Antibacterial activity	23
Lawsonia inermis	Leaves and bark	$Co(NO_3)_2{\cdot}6H_2O$	98 nm	Rough cubic and spherical	Bimedical	24

Mappia foetida	Leaves	$CoCl_2$	—	Spherical	Antimicrobial potential	25
Spent coffee	Seed	$Co(NO_3)_2\cdot 6H_2O$	29.01 nm	Spherical and irregular	Catalytic and photocatalytic dye degradation	26
Jasminum mesnyi	Leaves	$Co(NO_3)_2\cdot 6H_2O$	59.9 nm	Spherical	Degradation of dye	27
Celosia argentea	Whole plant	—	27.42 nm	—	—	28
Litchi chinensis	Fruit	$Co(OAc)_2\cdot 4H_2O$	26–40 nm	Spherical	—	29
Calotropis gigantea	Leaves	—	50 nm	Spherical	—	30
Calotropis procera	Latex	$Co(OAc)_2\cdot 4H_2O$	10 nm	Spherical	Antibacterial activity	31
Raphanus sativus var. longipinnatus	Leaves	—	80 nm	Spherical	—	32
Helianthus annuus	Leaves	—	—	Plate	—	33
Carica papaya	Leaves	$Co(NO_3)_2\cdot 6H_2O$	22 nm	Spherical	Anti-oxidant, anti-cancer	34
Piper nigrum	Seeds	$CoCl_2\cdot 6H_2O$	40–60 nm	Triangular-like with irregular spherical	—	35
Phoenix dactylifera	Seed	—	~80 nm	Spherical	Photocatalytic and antimicrobial	36
Citrus limon	Fruit juice	$CoCl_2\cdot 6H_2O$	—	—	Antimicrobial activity	37
Senna auriculata	Flower	$Co(NO_3)2\cdot 6H_2O$	31.94 nm	—	Antibacterial and antifungal	38
Manilkara zapota	Leaves	$Co(NO_3)2\cdot 6H_2O$	20.23 nm	—	Antifungal activity	39
Rhamnus virgata	Leaves	$Co(OAc)_2\cdot 4H_2O$	~17 nm	—	Biological applications	40
Spirulina platensis	Whole Plant	$CoCl_2\cdot 6H_2O$	13.28 nm	—	Antifungal activity	41
Withania coagulans	Plant	$CoCl_2\cdot 6H_2O$	49–59 nm	Bead, cube	Antibiotic, antifungal and biofilm activity	42
Gingko	Leaves	$Co(CH_3COO)_2$	30–100 nm	Irregular	Electrochemical biosensing	43
Abies pindrow	Leaves	$C_4H_6CoO_4\cdot 4H_2O$	17 nm	Spherical	dye degradation	44
Duranta repens	Leaves	$(CH_3COO)_2Co\cdot 4H_2O$	~23 nm	—	Electrochemical analysis of tramadol	45
Rosmarinus officinalis	Leaves	$Co(OAc)_2\cdot 4H_2O$	~6.5 nm	—	Biomedical and photocatalytic application	46
Hibiscus rosa sinensis	Flower	Co_3O_4	34.9 nm	Tubular like	Antibacterial activity	47
Spinacia Oleracea	Leaves	$CoCl_2\cdot 6H_2O$	—	Agglomerated-spherical	—	48
Vitis vinifera	Seed	$Co(NO_3)_2\cdot 6H_2O$	10–20 nm	Nanorod	Catalytic, photocatalytic, and antibacterial activities	49
Mollugo oppositifolia	Leaves	$CoCl_2\cdot 6H_2O$	22.7 nm	Spherical	Antimicrobial activity	50
Geranium wallichianum	Leaves	$Co(OAc)_2\cdot 4H_2O$	21 nm	—	Enzyme inhibition, antioxidant, cytotoxic and antimicrobial	51
Palm kernel	Seed	$CoCl_2\cdot 6H_2O$	9–22 nm	Diamond, hexagonal	—	52
Phytolacca dodecandra	Leaves	$Co(NO_3)_2\cdot 6H_2O$	10.79 nm	Spherical	Antimicrobial activity	53
Arishta	Leaves	$CoCl_2\cdot 6H_2O$	40–50 nm	—	Antibacterial, antifungal activity	54
Ziziphus oxyphylla	Root	$CoCl_2\cdot 6H_2O$	40–60 nm	Irregular and spherical	Antibacterial activity	55
Hibiscus rosa sinensis	Leaves	$C_4H_6CoO_4$	18.98 nm	Spherical or elliptical	Antibacterial, antioxidant	56
Cordia myxa	Leaves, roots, and fruit	$Co(NO_3)_2\cdot 6H_2O$	47–48 nm	Prism	Photocatalytic activity	57
Aerva javanica	Aerial	$CoCl_2\cdot 6H_2O$	39.23 nm	Poly shaped	Antimicrobial activity	58
Curcuma longa	Leaves	$Co(NO_3)_2\cdot 6H_2O$	22 nm	Spherical	Photocatalytic and antibacterial	59
Ipomoea carnea	Leaves	$CoCl_2\cdot 6H_2O$	6–10 nm	Spherical	Micronutrient and antimicrobial activity	60
Trigonella foenumgraceum	Leaves	$CoCl_2\cdot 6H_2O$	13.2 nm	Spherical	—	61
Aspalathus linearis	Leaves	$Co(NO_3)_2\cdot 6H_2O$	~3.6 nm	Quasi-spherical Cubic	—	62
Sageretia thea	Leaves	$Co(OAc)_2\cdot 4H_2O$	20.03 nm	Spherical Cubic	Antibacterial, antioxidant	63
Clitoria ternatea	Flower	$CoCl_3\cdot 6H_2O$	13–17 nm	Spherical	Antibacterial, antioxidant	64
Manihot esculenta	Root	$CoCl_2$	36 nm	Prism like-anchored octahedron	—	65
Aerva lanata	Leaves	$Co(NO_3)_2\cdot 6H_2O$	36.24 nm	Irregular, cubic, hexagonal, and spherical	Antimicrobial and antioxidant	66
Sesbania sesban	Plant	$Co(NO_3)_2\cdot 6H_2O$	15–30 nm	Spherical	Antibacterial, antioxidant	67
Populus ciliata	Leaves	$Co(NO_3)_2\cdot 6H_2O$	15–35 nm	Square	Antibacterial activity	68
Momordica charantia	Aerial	$CoCl_2\cdot 6H_2O$	40–90 nm	Irregular	Photocatalytic activity	69
Caccinia macranthera	Seed	$Co(NO_3)_2\cdot 6H_2O$	30–45 nm	Granular shape	Cytotoxicity and photocatalytic	70
Solanumlycopersicum	Seed	$Co(NO_3)_2\cdot 6H_2O$	5 nm	Quantum dot	Degradation of ciprofloxacin	71
Psidium guajava	Leaves	$Co(NO_3)_2\cdot 6H_2O$	26–40 nm	Spherical	Photocatalytic	72
Salvia hispanica	Leaves	$Co(NO_3)_2\cdot 6H_2O$	9.218nm	Spherical	Biomedical and photocatalytic	73
Ocimum tenuiflorum	Leaves	$Co(NO_3)_2\cdot 6H_2O$		Rod	Antifungal activity and sensing	74
Euphorbia tirucalli	stem	$CoSO_4\cdot 7H_2O$	1 mm- 100 nm	Irregular and spherical	Breast cancer inhibition	75
Rosmarinus officinalis	Leaves	$CoCl_2\cdot 6H_2O$	19–33 nm	Sheets like	Anticancer activity	76

Characterisation of plant-based synthesised Cobalt oxide NPs

Characterization of Cobalt Oxide Nanoparticles (Co_3O_4 NPs), which vary widely in size, shape, and surface area, relies on a diverse suite of analytical techniques. These methods include UV-visible spectroscopy, thermogravimetric analysis, Fourier transform infrared spectroscopy, powder X-ray diffraction, photoluminescence, and various microscopy and scattering techniques like SEM, TEM, AFM, DLS, and EDS. Spectroscopic and diffraction methods, such as UV-vis, XRD, FTIR, DLS, EDS, and Raman, are collectively used to determine the crystal size, lattice planes, phase, structural configuration, and elemental composition of the NPs. Specifically, EDS confirms the elemental makeup, while DLS measures particle size distribution and surface charge. Furthermore, XRD provides crystallite size information, and FTIR identifies surface functional groups (like flavonoids, phenols, and hydroxyls) that are essential for successful reduction and stabilization during nanoparticle synthesis.

Applications of Cobalt oxide NPs

Cobalt oxide nanoparticles (Co_3O_4 NPs) are characterized by their diversity, multi-faceted materials. It contains both regular and monoclinic structures. Their main useful properties are: high resistance to oxidation and corrosion associated with effective, non-toxic and environmentally friendly,due to these excellent properties, Co_3O_4 NPshave found wide application in many advanced fields. These applications primarily demonstrate their usefulnesssuch as photocatalytic treatment of wastewater, as well as Solar energy storage Tools and Supercapacitor [77]. In addition, Co_3O_4 NPs are involved in development ofMagnetic semiconductorsandElectrochemical sensorTechnology. The use of these nanoparticles in some areas such as photocatalytic environmental applications, water purification, electrochemical sensors and related applications [78]. Moreover, antimicrobial activity, cytotoxicity, antifungal and antioxidant activityare the areas that are specifically researched.

Degradation of water-based dyes

Dyes are complex chemicals with specific functional groups (auxo-chromates, chromophores, conjugated systems, etc.) and are widely used as dyes to produce attractive products such as textiles, paper, leather, etc. Therefore, it is of great importance to find an effective solution for the treatment of dye wastewater [79]. Interestingly, CoO-NPs have opened a new dimension in the treatment of wastewater due to their high adsorption and photocatalytic activity. In recent years, many studies have been published on the degradation or removal of dyes from wastewater using CoO-NPs. For example, Adekunle et al. [80] tested the photocatalytic degradation of eriochrome black-T and muroxide dyes in aqueous solution under the influence of sunlight. The authors showed that only 10 mg of nanoparticles showed good degradation efficiency within 40 min of sunlight exposure. Initially, the authors proposed the hypothesis that dye molecules interact with nanoparticles and initiate the color change process. Therefore, photocatalytic degradation of dye molecules occurs after prolonged exposure to sunlight. Similar observations were reported in the study done by Sonkusare et al. [81] for the photocatalytic degradation of malachite green, erythrochrome black-T, methyl red and bromophenol blue under visible light. The photocatalytic activity was evaluated using UV-visible spectra as a function of time before and after treatment with CoO-NPs and liquid chromatography-mass spectrometry (LC-MS) analytical methods. The authors observed excellent and rapid photocatalytic degradation (>95%) of selected dye molecules with a nanoparticle size of 50 mg within 40 min under visible irradiation. The main reasons for the excellent photocatalytic performance were the morphology of the metal nanoparticles, the energy gap compared to CoO nanoparticles, and the presence of electron holes. Under visible light irradiation, electrons in the valence band were excited and moved to the conduction band, where corresponding holes (h) were generated. Therefore, e-h pairs were generated at the active site of the cobalt nanoparticles, which were combined with the dye molecule through oxygen and water molecules. In this way, superoxide radical anion was generated, and reactive OH radicals were generated, which acted as strong oxidizing agents for the dye. In this way, the strong oxidizing radicals generated reacted with the aqueous dye solution and were converted into dyes by oxidation of the dye. In addition to the e-h coupling factor, the specific surface area, mesoporosity, and surface morphology were important factors in enhancing the photocatalytic degradation of dye molecules by CoO_2 nanoparticles. Furthermore, the authors identified the photocatalytic degradation products of the dyes in the reaction with cobalt nanoparticles by LC-MS analysis. The reduction products were observed after 15 minutes of reaction, and 100% degradation was observed within 45 minutes. In another recent study, Samuel et al. [82] evaluated the photocatalytic activity of CoO nanoparticles in the degradation of the acidic dye Blue-74 (a cationic dye) in aqueous solution in the presence of UV radiation. The photochemical activity of the acid dye Blue-74 increased tenfold at acidic pH values compared to the initial pH value, indicating that this is due to the presence of different charges on the surface of the nanoparticles. The key factors for the high photochemical degradation performance of nanoparticle catalysts under UV light are the appropriate doping of cobalt oxides to improve the photochemical efficiency and the functionality of other metal nanoparticles. CeO_2 nanoparticles (Co-CeO_2 NPs) were prepared by aqueous extraction of the bark of Salvadora persica from the Salvadora persica tree with trimethylamine, fluorine, fluorine compounds, isothiocyanate, sodium bicarbonate, tannin and sulphur compounds. This tree is rich in sulphur compounds. The nanoparticles (NPs) were tested for degradation in an aqueous solution of "Acid Orange 7".

The photovoltaic performance of the green composite nanoparticles was significantly improved by the addition of 7% cobalt (from 10 mg L1 to 95.4% at pH 5.0 in 180 min). Furthermore, the incorporation of 7% cobalt and cerium nanoparticles not only increased the surface area of the nanomaterial but also reduced the energy gap, thereby accelerating the photovoltaic efficiency.

Use of an electrochemical sensor

CoO-NP nanoparticles synthesized from plant extracts exhibit exceptional stability, good electroactive properties, and electrical conductivity. Due to their broad linear range, selectivity, low detection limit, and reliable performance, they are used in various electrochemical sensing applications [83]. For example, Sharma et al. [84] reported the use of bioreduction of cobalt nitrate and aqueous Nigella sativa seeds for the synthesis of CoO-NP nanoparticles. In this work, an aqueous solution of Nigella sativa (15 mL) was heated with cobalt nitrate, and the resulting mixture was heated at 85 °C for 30 min with constant stirring. Then, the resulting precipitate was washed with distilled water and ethanol, and dried at 80 °C for 10 h. The nanoparticles were further coated with Nafion (an ionic polymer) and applied to a glassy carbon electrode for electrochemical detection of hydrocortisone by cyclic voltammetry and differential pulse voltammetry. Hydrocortisone is an anti-inflammatory and anti-allergic glucocorticoid that is useful in the treatment of severe skin infections and inflammation in humans and animals. TEM analysis of the synthetic CoO_2 nanoparticles revealed a spherical morphology with a particle size of 2–18 nm and a diameter of 8.7 nm. The authors observed that Nafion significantly increased the active surface area of the CoO2 nanoparticles on the glassy carbon electrode. Therefore, the sensor showed a low detection limit of 0.001–1 µm for hydrocortisone and showed excellent recoveries (97.7%–102.5%) in blood serum samples and drug infusions. The authors reported that a hybrid system (Naf-CoO2/GCE) was fabricated by synthesizing Nafion-based CoO_2 nanoparticles from oxygen atoms on a glassy carbon electrode. Memon et al. [85] reported the synthesis of CoO-NP using the leaves of Duranta repens L., commonly known as the flower of paradise or golden dew. The crystallinity of the synthesized CoO-NP was investigated using the DB Scherrer equation based on the results of X-ray diffraction analysis.

Antibacterial effect

The emergence of drug-resistant bacteria is currently a global concern. Therefore, there is a need for antimicrobial agents that can kill bacteria that are resistant to existing drugs [86]. Nanoparticles are characterized by their small size and large surface area compared to larger particles and therefore have potent antimicrobial activity. Nanoparticles exhibit size-dependent membrane diffusion and inhibit bacterial protein synthesis by disrupting the cell membrane [87]. Gold, iron, silver, and iron oxides, such as iron oxide, cobalt oxide, and cobalt oxide, have shown significant antimicrobial activity. Silver nanoparticles are of interest not only in the biomedical industry but also in the food industry due to their antimicrobial properties [88]. Two important properties have been proposed. First, the positive sites of different cobalt ions on cobalt oxide nanoparticles, namely CO_2^+ and CO^{3+}, react with the negative charges of the cell membrane, leading to cell death. Second, electrons in cobalt oxide can be excited to the conduction and valence bands by light. In the conduction band, the reaction of oxygen molecules with electrons forms the superoxide radical anion. Eventually, hydrogen peroxide, a strong oxidizing agent, is produced. The reaction of water with the superoxide radical anion on cobalt oxide nanoparticles leads to the destruction of the cell membrane. Therefore, cobalt oxide nanoparticles can be effective antimicrobial agents even at low concentrations [92]. Cobalt and cobalt oxide nanoparticles have antimicrobial properties. Eltarakhoni et al. (2018) reported an eco-friendly synthesis of nanoparticles using the Gram-negative bacterium *P. mirabilis*. The nanoparticles were characterized by UV-Vis spectroscopy, EDX spectroscopy, XRD spectroscopy, TEM spectroscopy, dynamic light scattering (DLS) and polydispersity index (PDI). Antimicrobial activity was observed by diffusion methods against *S. typhi*, *E. coli, C. perfringens, S. aureus* and *Enterococcus faecalis* [89]. [19] synthesized hemispherical cobalt oxide nanoparticles with a diameter of 20–27 nm using the fungal species *Aspergillus brasiliensis*. This is the first time that fungal cobalt oxide nanoparticles have been synthesized and shown significant activity against multiple pathogens [90]. The biosynthesis of cobalt oxide nanoparticles using intact *Celosia argentina* has been reported several times, and their antibacterial activity has been investigated using the disk diffusion method. The synthesized nanoparticles were shown to be active against *B. subtilis* and *E. coli* [87]. Cobalt oxide nanoparticles were synthesized in vitro in green media with *Hibiscus rosa-sinensis* extract, and their antibacterial activity was measured. These green clay nanoparticles were shown to be active against *E. coli, Streptococcus mutans, S. aureus,* and *Klebsiella pneumoniae* [91].

Antifungal activity

Bacteria and fungi are developing resistance to antibiotics and existing drugs at an alarming rate. Therefore, there is a need for effective antifungal agents that can kill fungi that are resistant to existing drugs [1]. Cobalt and cobalt oxide nanoparticles have diverse biomedical applications due to their diverse properties, including antifungal properties. Hou et al. (2020) measured the antifungal properties of cobalt nanoparticles produced by an environmentally friendly process, and the results showed that cobalt nanoparticles exhibited potent fungicidal activity against *Candida krusei, Candida guilliermondi, Candida glabrata,* and *Candida albicans* [93]. Similarly, the synthesis of cobalt oxide nanoparticles from H. *rosa-sinensis* flower extract and their fungicidal activity were reported.

The results showed that the synthesized nanoparticles exhibited potent activity against *Aspergillusflavus* and *A. niger* [91].

Antioxidant activity

For cellular survival, Oxidative metabolism is an essential process. Nevertheless, the formation of free radicals and reactive oxygen species (ROS) is a damaging side effect of this process. When these harmful molecules build up, they trigger enzymes like catalase and superoxide dismutase, which in turn inflict damage on cellular proteins, membrane lipids, and DNA [94]. This destruction can be lethal to cells and disrupt their ability to respire. Outside the body, oxidation is a major chemical contaminant in food, degrading its quality, safety, and nutritional content. The good news is that both natural and man-made antioxidants are available to reduce the adverse impact of oxidation[95]. Antimicrobial experiments, free radical scavenging capacity, total antioxidant capacity and total reducing power were evaluated. Bio-derived cobalt oxide nanoparticles showed excellent radical scavenging capacity, moderate total antioxidant capacity and total reducing power [96]. Shahzadi et al. (2019) also investigated the radical scavenging capacity of bio-derived CoNPs and reported that the radical scavenging capacity and antioxidant activity were dependent on the CoNP concentration: increasing the concentration led to an increase in the CoNP concentration [87]. Nanoparticles were synthesized using lamellar leaves of *Ziziphora clinopodioides,* and their antioxidant activity was evaluated. The synthesized green nanoparticles showed significant results and had good DPPH scavenging activity [93]. Similarly, cobalt oxide nanoparticles made from *Sesbania sesbana* extract showed lower DPPH radical scavenging activity compared to silver and copper oxide nanoparticles [67].

Conclusion

Cobalt and cobalt oxide nanoparticles (NPs) synthesised by environmentally friendly (green) methods offer a wide range of biological and biomedical applications. Traditionally, NPs have been produced by expensive physical or chemical processes, which often lead to environmental pollution. In contrast, green synthetic methods use natural resources - plant extracts or plant parts, microorganisms, or biomolecules - such as oleic acid, secondary metabolites, flavonoids, pigments, proteins and starch-to synthesizenanoparticles. Biosynthetic methods can produce not only cobalt and cobalt oxide NPs but also cheap and easy to build but they are still Eco-friendly that serves as Biocompatible.

References

1. Ahmad, S., Munir, S., Zeb, N., Ullah, A., Khan, B., Ali, J., ... & Ali, S. (2019). Green nanotechnology: A review on green synthesis of silver nanoparticles—An ecofriendly approach. International journal of nanomedicine, 5087-5107.
2. Gurunathan, S., Lee, A. R., & Kim, J. H. (2022). Antifungal effect of nanoparticles against COVID-19 linked black fungus: a perspective on biomedical applications. International Journal of Molecular Sciences, 23(20), 12526.
3. Iravani, S., Korbekandi, H., Mirmohammadi, S. V., & Zolfaghari, B. (2014). Synthesis of silver nanoparticles: chemical, physical and biological methods. Research in pharmaceutical sciences, 9(6), 385-406.
4. Ovais, M., Khalil, A. T., Islam, N. U., Ahmad, I., Ayaz, M., Saravanan, M., ... & Mukherjee, S. (2018). Role of plant phytochemicals and microbial enzymes in biosynthesis of metallic nanoparticles. Applied microbiology and biotechnology, 102(16), 6799-6814.
5. Kumar, S., Kaur, A., Gaur, J., Singh, P., Kaur, H., Kaushal, S., ... & Misra, M. (2025). State-of-the-Art in Co_3O_4 Nanoparticle Synthesis and Applications: Toward a Sustainable Future. ChemistrySelect, 10(6), e202405147.
6. Zallouz, S., Réty, B., Vidal, L., Le Meins, J. M., & Matei Ghimbeu, C. (2021). Co3O4 nanoparticles embedded in mesoporous carbon for supercapacitor applications. ACS Applied Nano Materials, 4(5), 5022-5037.
7. Al-Enazi, N. M., Alsamhary, K., Ameen, F., & Kha, M. (2023). Plant extract-mediated synthesis cobalt doping in zinc oxide nanoparticles and their in vitro cytotoxicity and antibacterial performance. Heliyon, 9(9).
8. Waris, A., Din, M., Ali, A., Afridi, S., Baset, A., Khan, A. U., & Ali, M. (2021). Green fabrication of Co and Co3O4 nanoparticles and their biomedical applications: A review. Open life sciences, 16(1), 14-30.
9. Satpathy, B., Sa, N., Behera, A., & Sahu, P. K. (2025). Dose-dependent attenuation of the efficacy of Clitoria ternatea by cobalt oxide nanoparticles against diabetes-induced cognitive impairment. Molecular Neurobiology, 62(2), 2601-2616.
10. Akinsiku, A. A., Odaudu, R. O., De Campos, O. C., Adeyemi, A. O., & Ejilude, O. (2023). Synthesis of low toxic silver-cobalt nanoparticles using Annona muricata leaf extract: Antimicrobial evaluation. Inorganic Chemistry Communications, 153, 110837.
11. Diallo, A., Beye, A. C., Doyle, T. B., Park, E., & Maaza, M. (2015). Green synthesis of Co3O4 nanoparticles via Aspalathus linearis: physical properties. Green Chemistry Letters and Reviews, 8(3-4), 30-36.
12. Pagar, T., Ghotekar, S., Pagar, K., Pansambal, S., & Oza, R. (2019). A review on bio-synthesized Co3O4 nanoparticles using plant extracts and their diverse applications. Journal of Chemical Reviews, 1(4), 260-270.
13. AlSalhi, M. S., Oza, G., Castillo-Maldonado, I., & Sharma, A. (2024). Evaluation of antimicrobial, antioxidant, and anti-inflammatory abilities of sustainably synthesized Co3O4 NPs. Biocatalysis and Agricultural Biotechnology, 56, 103025.
14. Faisal, S., Jan, F. A., Saleem, S., Ullah, R., Wajidullah, Ullah, N., & Salman. (2022). Juglans regia L. mediated synthesis of cobalt oxide and zinc-doped cobalt oxide nanoparticles: characterization and evaluation for environmental, antibacterial and cytotoxic potential. Nanotechnology for Environmental Engineering, 7(3), 675-689.
15. Kshirsagar, A. K., Bhutekar, P. G., Bankar, S. S., More, R. T., More, S. T., Mirgane, S. R., & Adm, E. (2024). Green synthesis, characterization, and antimicrobial activities of manganese dioxide and cobalt oxide nanoparticles from Blumea lacera leaf extract. Educational Administration: Theory and Practice, 30(1), 3149–3154.

16. Chole, P., & Manjunath, B. T. (2024). Green synthesis of cobalt oxide nanoparticles with in-vitro cytotoxicity assessment using pomegranate (Punica granatum L.) seed oil: A promising approach for antimicrobial and anticancer applications.
17. Sivagnanam, N., Pichai, S., Perumal, P., & Kandan, V. (2024). Photocatalytic and antibacterial activity of green synthesized yttrium doped cobalt oxide nanoparticles using tender coconut water (Cocos nucifera). Chemical Papers, 78(9), 5527-5544.
18. Sarkar, D. K., Selvanathan, V., Mottakin, M., Islam, M. A., Almohamadi, H., Alharthi, N. H., & Akhtaruzzaman, M. (2024). Phytochemicals assisted green synthesis of copper oxide/cobalt oxide as efficient electrocatalyst for oxygen evolution reaction. International Journal of Hydrogen Energy, 51, 700-712.
19. Alemu, F. W., & Zeleke, T. D. (2024). Green synthesis of silver and cobalt oxide nanoparticles using Croton macrostachyus plant extract and evaluation of their antibacterial activity. Nanomedicine Journal, 11(1).
20. Alshareef, S. A., & Albalawi, A. E. (2024). Unveiling the diverse bioactivity of cobalt oxide nanoparticles produced through carboxymethyl cellulose extraction. International Journal of Biological Macromolecules, 279, 135028.
21. Ahmed, K., Tariq, I., & Mudassir, S. U. S. M. (2021). 11. Green synthesis of cobalt nanoparticles by using methanol extract of plant leaf as reducing agent. Pure and Applied Biology (PAB), 5(3), 453-457.
22. Kavica, S., Rajesh, P., Velmani, V., & Parethe, G. T. (2024). Biological synthesis of cobalt oxide nanoparticles using Ziziphus oenopolia leaf extract. J Environ Nanotechnol, 13, 85-91.
23. Urabe, A. A., & Aziz, W. J. (2019). Biosynthesis of cobalt oxide (Co3O4) nanoparticles using plant extract of Camellia sinensis (L.) Kuntze and Apium graveolens L. as the antibacterial application. World News of Natural Sciences, (24), 356-364.
24. Kolahalam, L. A., Prasad, K. R. S., Krishna, P. M., & Supraja, N. (2024). Lawsonia inermis plant-based cobalt oxide nanoparticles: synthesis, characterization and their biological studies. Results in Chemistry, 7, 101367.
25. Patil, J. B., Takate, S. J., Moharekar, S. T., Zaware, B. H., & Moharekar, S. S. (2021). Green synthesis of Co3O4 nanoparticles using mappia foetida leaf extract and its antimicrobial potential. Oriental Journal of Chemistry, 37(4), 979.
26. Drummer, S., Mkhari, O., & Chowdhury, M. (2024). Green synthesis of Co3O4 nanoparticles using spent coffee: Application in catalytic and photocatalytic dye degradation. Next Nanotechnology, 6, 100069.
27. Zeb, M., Anjum, Z., Mumtaz, S., Khalid, M., & Hafeez, M. (2024). Jasminum mesyni mediated synthesis of Co3O4/NiO nanocomposite for methylene blue degradation. Desalination and Water Treatment, 317, 100165.
28. Shahzadi, T., Zaib, M., Riaz, T., Shehzadi, S., Abbasi, M. A., & Shahid, M. (2019). Synthesis of eco-friendly cobalt nanoparticles using Celosia argentea plant extract and their efficacy studies as antioxidant, antibacterial, hemolytic and catalytical agent. Arabian Journal for Science and Engineering, 44(7), 6435-6444.
29. Onwudiwe, D. C., Ravele, M. P., & Elemike, E. E. (2020). Eco-friendly synthesis, structural properties and morphology of cobalt hydroxide and cobalt oxide nanoparticles using extract of Litchi chinensis. Nano-Structures & Nano-Objects, 23, 100470.
30. Sharma, J. K., Srivastava, P., Singh, G., Akhtar, M. S., & Ameen, S. J. M. S. (2015). Green synthesis of Co3O4 nanoparticles and their applications in thermal decomposition of ammonium perchlorate and dye-sensitized solar cells. Materials Science and Engineering: B, 193, 181-188.
31. Dubey, S., Kumar, J., Kumar, A., & Sharma, Y. C. (2018). Facile and green synthesis of highly dispersed cobalt oxide (Co3O4) nano powder: Characterization and screening of its eco-toxicity. Advanced Powder Technology, 29(11), 2583-2590.
32. Koyyati, R., Kudle, K. R., & Padigya, P. R. M. (2016). Evaluation of antibacterial and cytotoxic activity of green synthesized cobalt nanoparticles using Raphanus sativus var. longipinnatus leaf extract. Int. J. Pharmtech Res, 9(3), 466-72.
33. Saeed, M., Akram, N., Naqvi, S. A. R., Usman, M., Abbas, M. A., Adeel, M., & Nisar, A. (2019). Green and eco-friendly synthesis of Co3O4 and Ag-Co3O4: Characterization and photo-catalytic activity. Green Processing and Synthesis, 8(1), 382-390.
34. Krishnan, S. T., Parveen, S., El Newehy, A. S., Chandramohan, G., & Kalaiarasi, G. (2024). Green approaches for the synthesis of nickel oxide and cobalt oxide nanoparticles towards anti-oxidant and anti-cancer applications. Journal of the Indian Chemical Society, 101(8), 101187.
35. Saravanakumar, P., Muthukumar, M., Muthuchudarkodi, R. R., & Ramkumar, P. (2018). Piper nigrum mediated green synthesis, characterization of undoped cobalt oxide and cerium ion doped cobalt oxide nanoparticles. Int J Recent Res Aspects, 918-23.
36. Rajeswari, V. D., Khalifa, A. S., Elfasakhany, A., Badruddin, I. A., Kamangar, S., & Brindhadevi, K. (2023). Green and ecofriendly synthesis of cobalt oxide nanoparticles using Phoenix dactylifera L: Antimicrobial and photocatalytic activity. Applied Nanoscience, 13(2), 1367-1375.
37. Anuradha, C. T., & Raji, P. (2021). Citrus limon fruit juice-assisted biomimetic synthesis, characterization and antimicrobial activity of cobalt oxide (Co3O4) nanoparticles. Applied Physics A, 127(1), 55.
38. Anuradha, C. T., & Raji, P. (2023). Bio-inspired Senna auriculata flower extract assisted biogenic synthesis, characterization of cobalt oxide nanoparticles and their antibacterial and antifungal efficacy. Ceramics International, 49(7), 11689-11695.
39. Manzoor, S., Yasmin, G., Raza, N., Fernandez, J., Atiq, R., Chohan, S., ... & Azam, M. (2021). Synthesis of polyaniline coated magnesium and cobalt oxide nanoparticles through eco-friendly approach and their application as antifungal agents. Polymers, 13(16), 2669.
40. Abbasi, B. A., Iqbal, J., Khan, Z., Ahmad, R., Uddin, S., Shahbaz, A., ... & Mahmood, T. (2021). Phytofabrication of cobalt oxide nanoparticles from Rhamnus virgata leaves extract and investigation of different bioactivities. Microscopy Research and Technique, 84(2), 192-201.

41. Sidorowicz, A., Margarita, V., Fais, G., Pantaleo, A., Manca, A., Concas, A., ... & Cao, G. (2022). Characterization of nanomaterials synthesized from Spirulina platensis extract and their potential antifungal activity. PLoS One, 17(9), e0274753.
42. Hasan, M., Zafar, A., Shahzadi, I., Luo, F., Hassan, S. G., Tariq, T., ... & Shu, X. (2020). Fractionation of biomolecules in Withania coagulans extract for bioreductive nanoparticle synthesis, antifungal and biofilm activity. Molecules, 25(15), 3478.
43. Han, L., Yang, D. P., & Liu, A. (2015). Leaf-templated synthesis of 3D hierarchical porous cobalt oxide nanostructure as direct electrochemical biosensing interface with enhanced electrocatalysis. Biosensors and Bioelectronics, 63, 145-152.
44. Shaheen, I., & Ahmad, K. S. (2020). Green synthesis of doped Co3O4 nanocatalysts using organic template for fast azo dye degradation from aqueous environment. Journal of Chemical Technology & Biotechnology, 95(11), 2898-2910.
45. Memon, S. A., Hassan, D., Buledi, J. A., Solangi, A. R., Memon, S. Q., & Palabiyik, I. M. (2020). Plant material protected cobalt oxide nanoparticles: sensitive electro-catalyst for tramadol detection. Microchemical Journal, 159, 105480.
46. Sani, A., Murad, A., Hassan, D., Channa, G. M., El-Mallul, A., & Medina, D. I. (2023). Photo-catalytic and biomedical applications of one-step, plant extract-mediated green-synthesized cobalt oxide nanoparticles. Environmental Science and Pollution Research, 30(8), 20736-20745.
47. Ogunyemi, S. O., Xu, X., Xu, L., Abdallah, Y., Rizwan, M., Lv, L., ... & Li, B. (2023). Cobalt oxide nanoparticles: An effective growth promoter of Arabidopsis plants and nano-pesticide against bacterial leaf blight pathogen in rice. Ecotoxicology and Environmental Safety, 257, 114935.
48. Ahmed, Y., Hussain, J., & Asif, S. (2020). Green synthesis of Copper oxide and Cobalt oxide nanoparticles using Spinacia Oleracea leaf extract.
49. Kombaiah, K., Vijaya, J. J., Kennedy, L. J., Kaviyarasu, K., Ramalingam, R. J., & Al-Lohedan, H. A. (2019). Green synthesis of Co3O4 nanorods for highly efficient catalytic, photocatalytic, and antibacterial activities. Journal of nanoscience and nanotechnology, 19(5), 2590-2598.
50. Gowthami, P., Kosiha, A., Meenakshi, S., Boopathy, G., Ramu, A. G., & Choi, D. (2023). Biosynthesis of Co3O4 nanomedicine by using Mollugo oppositifolia L. aqueous leaf extract and its antimicrobial, mosquito larvicidal activities. Scientific Reports, 13(1), 9002.
51. Iqbal, J., Abbasi, B. A., Batool, R., Khalil, A. T., Hameed, S., Kanwal, S., ... & Mahmood, T. (2019). Biogenic synthesis of green and cost effective cobalt oxide nanoparticles using Geranium wallichianum leaves extract and evaluation of in vitro antioxidant, antimicrobial, cytotoxic and enzyme inhibition properties. Materials Research Express, 6(11), 115407.
52. Ngnintedem Yonti, C., Kenfack Tsobnang, P., Lontio Fomekong, R., Devred, F., Mignolet, E., Larondelle, Y., ... & Lambi Ngolui, J. (2021). Green synthesis of iron-doped cobalt oxide nanoparticles from palm kernel oil via co-precipitation and structural characterization. Nanomaterials, 11(11), 2833.
53. Sabir, F. K., Bekele, E. T., Gonfa, B. A., Edossa, G. D., & Adino, A. T. (2021). Synthesis of cobalt oxide nanoparticles through chemical and biological pathways for antibacterial activity. Journal of Nanostructures, 11(3), 577-587.
54. Anuradha, C. T., & Raji, P. (2022). Facile-synthesis and characterization of cobalt oxide (Co3O4) nanoparticles by using Arishta leaves assisted biological molecules and its antibacterial and antifungal activities. Journal of Molecular Structure, 1262, 133065.
55. Mazhar, K., Saeed, S. Y., Raees, L., Mukhtiar, A., Khan, F., & Khan, M. (2022). Green synthesis of cobalt oxide nanoparticles using roots extract of Ziziphus Oxyphylla Edegew its characterization and antibacterial activity. Materials Research Express, 9(10), 105001.
56. Khan, M. A., Ali, F., Faisal, S., Rizwan, M., Hussain, Z., Zaman, N., ... & Bibi, N. (2021). Exploring the therapeutic potential of Hibiscus rosa sinensis synthesized cobalt oxide (Co3O4-NPs) and magnesium oxide nanoparticles (MgO-NPs). Saudi Journal of Biological Sciences, 28(9), 5157-5167.
57. Batool, S., Hasan, M., Dilshad, M., Zafar, A., Tariq, T., Shaheen, A., ... & Caprioli, G. (2022). Green synthesized ZnO-Fe2O3-Co3O4 nanocomposite for antioxidant, microbial disinfection and degradation of pollutants from wastewater. Biochemical Systematics and Ecology, 105, 104535.
58. Mubraiz, N., Bano, A., Mahmood, T., & Khan, N. (2021). Microbial and plant assisted synthesis of cobalt oxide nanoparticles and their antimicrobial activities. Agronomy, 11(8), 1607.
59. Chelliah, P., Wabaidur, S. M., Sharma, H. P., Jweeg, M. J., Majdi, H. S., AL. Kubaisy, M. M. R., ... & Lai, W. C. (2023). Green synthesis and characterizations of cobalt oxide nanoparticles and their coherent photocatalytic and antibacterial investigations. Water, 15(5), 910.
60. Upadhyay, D. D., Singh, S., Singh, K. B., Gautam, N., Shrivastava, S., & Pandey, G. (2023). Biogenically produced Co3O4 nanoparticles and their application as micronutrient and antimicrobial agent for agro-environmental sustainability. Inorganic Chemistry Communications, 155, 110957.
61. Akhlaghi, N., Najafpour-Darzi, G., & Younesi, H. (2020). Facile and green synthesis of cobalt oxide nanoparticles using ethanolic extract of Trigonella foenumgraceum (Fenugreek) leaves. Advanced Powder Technology, 31(8), 3562-3569.
62. Diallo, A., Beye, A. C., Doyle, T. B., Park, E., & Maaza, M. (2015). Green synthesis of Co3O4 nanoparticles via Aspalathus linearis: physical properties. Green Chemistry Letters and Reviews, 8(3-4), 30-36.
63. Khalil, A. T., Ovais, M., Ullah, I., Ali, M., Shinwari, Z. K., & Maaza, M. (2020). Physical properties, biological applications and biocompatibility studies on biosynthesized single phase cobalt oxide (Co3O4) nanoparticles via Sageretia thea (Osbeck.). Arabian Journal of Chemistry, 13(1), 606-619.
64. Parethe, G. T., Rajesh, P., Nathiya, P., Balaji, M., & Kavica, S. (2023). Green synthesis of cobalt oxide nanoparticles from Clitoria ternatea flower extracts its characterization and biological activities. World J. Adv. Res. Rev, 19.

65. Ikhuoria, E. U., Omorogbe, S. O., Sone, B. T., & Maaza, M. (2018). Bioinspired shape controlled antiferromagnetic Co3O4 with prism like-anchored octahedron morphology: A facile green synthesis using Manihot esculenta Crantz extract. Science and Technology of Materials, 30(2), 92-98.
66. Sahu, M., Singh, S., Prajapati, S., Verma, D. K., & Shin, D. K. (2024). From green chemistry to biomedicine: the sustainable symphony of cobalt oxide nanoparticles. RSC advances, 14(45), 32733-32758.
67. Ghadi, F. E., Ghara, A. R., & Naeimi, A. (2018). Phytochemical fabrication, characterization, and antioxidant application of copper and cobalt oxides nanoparticles using Sesbania sesban plant. Chemical Papers, 72(11), 2859-2869.
68. Hafeez, M., Shaheen, R., Akram, B., Haq, S., Mahsud, S., Ali, S., & Khan, R. T. (2020). Green synthesis of cobalt oxide nanoparticles for potential biological applications. Materials Research Express, 7(2), 025019.
69. Govindasamy, R., Raja, V., Singh, S., Govindarasu, M., Sabura, S., Rekha, K., ... & Thiruvengadam, M. (2022). Green synthesis and characterization of cobalt oxide nanoparticles using Psidium guajava leaves extracts and their photocatalytic and biological activities. Molecules, 27(17), 5646.
70. Mohandes, A., Aghamaali, M. R., Sabouri, Z., & Darroudi, M. (2023). Biosynthesis of cobalt oxide nanoparticles (Co3O4-NPs) using Caccinia macranthera extract and evaluation of their cytotoxicity and photocatalytic activity. Materials Science and Engineering: B, 297, 116782.
71. Bronzato, J. D., Bronzato, J. D., Brito, A. M., Bettini, J., Passini, M. R., Gomes, B. P., & Nantes, I. L. (2023). Degradation of ciprofloxacin by green cobalt oxide quantum dots. Applied Surface Science, 609, 155193.
72. Govindasamy, R., Raja, V., Singh, S., Govindarasu, M., Sabura, S., Rekha, K., ... & Thiruvengadam, M. (2022). Green synthesis and characterization of cobalt oxide nanoparticles using Psidium guajava leaves extracts and their photocatalytic and biological activities. Molecules, 27(17), 5646.
73. Kiani, M., Rabiee, N., Bagherzadeh, M., Ghadiri, A. M., Fatahi, Y., Dinarvand, R., & Webster, T. J. (2021). Improved green biosynthesis of chitosan decorated Ag-and Co3O4-nanoparticles: A relationship between surface morphology, photocatalytic and biomedical applications. Nanomedicine: Nanotechnology, Biology and Medicine, 32, 102331.
74. Muthukumar, T., Arumugam, E., Chandrasekaran, S., Karuppiah, C., & Kodirajan, S. (2021). Phytogenic synthesis of Co3O4 nanorods and its application in biomolecule sensing and antifungal activity. Inorganic Chemistry Communications, 123, 108305.
75. Kgosiemang, I. K., Lefojane, R., Direko, P., Madlanga, Z., Mashele, S., & Sekhoacha, M. (2020). Green synthesis of magnesium and cobalt oxide nanoparticles using Euphorbia tirucalli: Characterization and potential application for breast cancer inhibition. Inorganic and Nano-Metal Chemistry, 50(11), 1070-1080.
76. Al-Qasmi, N. (2022). Sustainable and efficacy approach of green synthesized cobalt oxide (Co3O4) nanoparticles and evaluation of their cytotoxicity activity on cancerous cells. Molecules, 27(23), 8163.
77. Dubey, S., Kumar, J., Kumar, A., & Sharma, Y. C. (2018). Facile and green synthesis of highly dispersed cobalt oxide (Co3O4) nano powder: Characterization and screening of its eco-toxicity. Advanced Powder Technology, 29(11), 2583-2590.
78. Samuel, M. S., Selvarajan, E., Mathimani, T., Santhanam, N., Phuong, T. N., Brindhadevi, K., & Pugazhendhi, A. (2020). Green synthesis of cobalt-oxide nanoparticle using jumbo Muscadine (Vitis rotundifolia): Characterization and photo-catalytic activity of acid Blue-74. Journal of Photochemistry and Photobiology B: Biology, 211, 112011.
79. Nasab, N. K., Sabouri, Z., Ghazal, S., & Darroudi, M. (2020). Green-based synthesis of mixed-phase silver nanoparticles as an effective photocatalyst and investigation of their antibacterial properties. Journal of Molecular Structure, 1203, 127411.
80. Adekunle, A. S., Oyekunle, J. A., Durosinmi, L. M., Oluwafemi, O. S., Olayanju, D. S., Akinola, A. S., ... & Ajayeoba, T. A. (2020). Potential of cobalt and cobalt oxide nanoparticles as nanocatalyst towards dyes degradation in wastewater. Nano-Structures & Nano-Objects, 21, 100405.
81. Sonkusare, V. N., Chaudhary, R. G., Bhusari, G. S., Mondal, A., Potbhare, A. K., Mishra, R. K., ... & Abdala, A. A. (2020). Mesoporous octahedron-shaped tricobalt tetroxide nanoparticles for photocatalytic degradation of toxic dyes. ACS omega, 5(14), 7823-7835.
82. Samuel, M. S., Selvarajan, E., Mathimani, T., Santhanam, N., Phuong, T. N., Brindhadevi, K., & Pugazhendhi, A. (2020). Green synthesis of cobalt-oxide nanoparticle using jumbo Muscadine (Vitis rotundifolia): Characterization and photo-catalytic activity of acid Blue-74. Journal of Photochemistry and Photobiology B: Biology, 211, 112011.
83. Agnihotri, A. S., & Varghese, A. (2021). Transition metal oxides in electrochemical and bio sensing: A state-of-art review. Applied Surface Science Advances, 4, 100072.
84. Sharma, N., Reddy, A. S., & Yun, K. (2021). Electrochemical detection of hydrocortisone using green-synthesized cobalt oxide nanoparticles with nafion-modified glassy carbon electrode. Chemosphere, 282, 131029.
85. Memon, S. A., Hassan, D., Buledi, J. A., Solangi, A. R., Memon, S. Q., & Palabiyik, I. M. (2020). Plant material protected cobalt oxide nanoparticles: sensitive electro-catalyst for tramadol detection. Microchemical Journal, 159, 105480.
86. Kapil, A. (2005). The challenge of antibiotic resistance: need to contemplate. Indian Journal of Medical Research, 121(2), 83.
87. Shahzadi, T., Zaib, M., Riaz, T., Shehzadi, S., Abbasi, M. A., & Shahid, M. (2019). Synthesis of eco-friendly cobalt nanoparticles using Celosia argentea plant extract and their efficacy studies as antioxidant, antibacterial, hemolytic and catalytical agent. Arabian Journal for Science and Engineering, 44(7), 6435-6444.
88. Mikołajczuk-Szczyrba, A., Kieliszek, M., Giurgiulescu, L., & Sokołowska, B. (2019). CHARACTERISTICS AND APPLICATION OF SILVER NANOPARTICLES IN THE FOOD INDUSTRY-REVIEW. Carpathian Journal of Food Science & Technology, 11(4).
89. Eltarahony, M., Zaki, S., ElKady, M., & Abd-El-Haleem, D. (2018). Biosynthesis, characterization of some combined nanoparticles, and its biocide potency against a broad spectrum of pathogens. Journal of Nanomaterials, 2018(1), 5263814.

90. Omran, B. A., Nassar, H. N., Younis, S. A., El-Salamony, R. A., Fatthallah, N. A., Hamdy, A., ... & El-Gendy, N. S. (2020). Novel mycosynthesis of cobalt oxide nanoparticles using Aspergillus brasiliensis ATCC 16404—optimization, characterization and antimicrobial activity. Journal of applied microbiology, 128(2), 438-457.
91. Anuradha, C. T., & Raji, P. J. M. R. E. (2019). Effect of annealing temperature on antibacterial, antifungal and structural properties of bio-synthesized Co3O4 nanoparticles using Hibiscus Rosa-sinensis. Materials Research Express, 6(9), 095063.
92. Iravani, S., & Varma, R. S. (2020). Sustainable synthesis of cobalt and cobalt oxide nanoparticles and their catalytic and biomedical applications. Green Chemistry, 22(9), 2643-2661.
93. Hou, H., Mahdavi, B., Paydarfard, S., Zangeneh, M. M., Zangeneh, A., Sadeghian, N., ... & Sen, F. (2020). Retracted article: novel green synthesis and antioxidant, cytotoxicity, antimicrobial, antidiabetic, anticholinergics, and wound healing properties of cobalt nanoparticles containing Ziziphoraclinopodioides Lam leaves extract. Scientific reports, 10(1), 12195.
94. Bauer, V., Sotnikova, R., Machova, J., Matyas, S., Pucovský, V., & Štefek, M. (1999). Reactive oxygen species induced smooth muscle responses in the intestine, vessels and airways and the effect of antioxidants. Life sciences, 65(18-19), 1909-1917.
95. Antolovich, M., Prenzler, P. D., Patsalides, E., McDonald, S., & Robards, K. (2002). Methods for testing antioxidant activity. Analyst, 127(1), 183-198.
96. Khalil, A. T., Ovais, M., Ullah, I., Ali, M., Shinwari, Z. K., & Maaza, M. (2020). Physical properties, biological applications and biocompatibility studies on biosynthesized single phase cobalt oxide (Co3O4) nanoparticles via Sageretiathea (Osbeck.). Arabian Journal of Chemistry, 13(1), 606-619.