

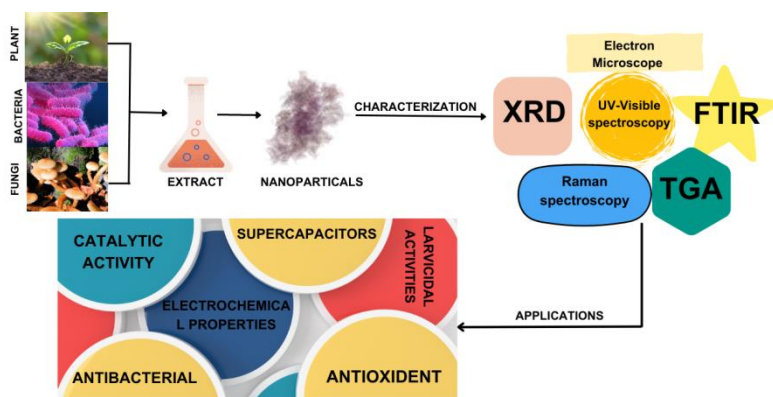
Review | <http://dx.doi.org/10.17807/orbital.v19i4.19437>

Biosynthesis of CoNPs: An Overview

Vaibhav Saini , Ajay Thakur , Monika Verma* , Ruchi Bharti , and Renu Sharma 

Nanotechnology encompasses the scientific exploration of material characteristics at the nanoscale, with a profound reliance on factors such as size, shape, and morphology. Its far-reaching potential holds the capacity to reshape numerous global industries and technologies, including healthcare, electronics, cosmetics, chemicals, energy, and composites. Nonetheless, conventional synthesis methods, predominantly chemical and physical, are progressively revealing their limitations over time. Consequently, a pressing imperative arises to investigate alternative strategies that enable the fabrication of NPs devoid of environmental hazards. Developing eco-friendly approaches for Nanoparticles (NPs) synthesis stands as a pivotal catalyst in advancing the principles of green chemistry. Presently, plant-based extraction methods have effectively demonstrated their efficacy in the synthesis of Cobalt nanoparticles (CoNPs). This succinct review presents an inclusive overview of the methodologies, advantages, and recent research endeavors about producing CoNPs employing green synthesis approaches involving plants, bacteria, and fungi.

Graphical abstract



Keywords

Biological materials
CoNPs
Green synthesis
Nanotechnology
Plant extraction
Synthesis methods

Article history

Received 18 Sep 2023
Revised 31 Jan 2024
Accepted 28 May 2024
Available online 31 Dec 2024

Handling Editor: Grégoire Demets

1. Introduction

The properties of Nanoparticles are greatly affected by their characteristics such as size, shape, and morphology. Advancements in the nanotechnology domain offer significant opportunities for enhancing quantity, quality and reducing the manufacturing costs of NPs [1]. Nanoparticles (NPs) are extremely small structures found in the nanoscale range, typically spanning dimensions from 1 to 100 nanometres [2]. Their diminutive size distinguishes them from commonplace materials, imparting exceptional properties and behaviors at this scale. NPs exhibit a diverse composition,

encompassing metals, metal oxides, polymers, and biological substances [3]. Their minute dimensions give rise to discernible physical, chemical, and biological attributes that deviate from their larger counterparts. The main feature of NPs is their ability to increase their surface area, which enhances their reactivity and increases surface interactions. These minuscule entities find versatile applications across numerous disciplines, encompassing medicine [4], drug delivery systems [5], catalysts [6], sensors [7] and cutting-edge materials [8].

Over the last two decades, numerous methods have been devised, and ongoing research continues to drive further advancements in the synthesis of NPs. Within the literature, different synthesis methods for NPs have been categorized into two main classes: top-down [9-19] and bottom-up [20-39] approaches using various methodologies. In this review paper, primary attention is focused on the green synthesis methods mainly involving biological entities to get the cobalt nanoparticles (CoNPs).

CoNPs refer to nanoscale particles composed of cobalt; a transition metal known for its unique properties. CoNPs have gained significant importance in various fields, including catalysis [40], energy storage [41], biomedicine, and environmental applications [42]. CoNPs have proven to be very beneficial as a catalysts for various chemical reactions [43]. They have been utilized in hydrogenation [44] and oxidation [45], contributing to developing more sustainable and efficient chemical processes. They exhibit excellent electrochemical properties, making them suitable for lithium-ion batteries and supercapacitors [46]. Their magnetic properties allow them to be used as a contrast agent for magnetic resonance imaging and be functionalized to deliver drugs [47] or therapeutic agents to specific targets in the body, improving drug efficacy and reducing side effects [48].

Additionally, CoNPs play a crucial role in environmental applications [49]. They can be adsorbents for removing pollutants and heavy metals from contaminated water sources [50]. The high surface area of these NPs allows for effective adsorption, helping in water purification and remediation efforts [51]. Keeping in view the benefits associated with CoNPs we are summarizing the green synthetic methodologies reported.

2. Green Synthesis Methods for CoNPs

The conventional physical and chemical methods for synthesizing CoNPs have several drawbacks, such as using or discharging toxic and costly chemicals that cause significant threats to the ecosystem. Moreover, these methods are associated with high energy consumption, costly processes, and time-intensive procedures. To address these challenges, researchers have shifted towards green synthesis of NPs, which offers an eco-friendly and biocompatible alternative with numerous advantages over traditional approaches [52,53].

The green-mediated synthesis of CoNPs involves various biological entities such as plants, different plant parts, biological molecules, fungi, and bacteria, as shown in Fig.1. These entities function as reducing agent as well as act as capping, or oxidize agents in the synthesis process [54–55]. Various microorganisms, plants, and other biological molecules have proven to be effective in the fabrication of CoNPs. The extensive availability of these substrates makes them a perfect fit for synthesizing CoNPs [56]. Plant-mediated synthesis offers a viable, commercially feasible, eco-friendly, reliable, waste-free, and straightforward alternative to complex and costly physicochemical processes [57,58].

Various parts of plants, including seeds, fruits, peels, shells, roots, stems, latex, and inner plant components, have been extensively utilized in synthesizing CoNPs. These plant parts serve as effective sources for the synthesis, leveraging their inherent chemical compositions and phytochemical profiles. Plant extracts contain diverse compounds such as amino acids, terpenoids, thymol, phenolic acid polysaccharides, etc. These metabolites are crucial as chelating and stabilizing, hydrogen donors, and metal-

chelating agents. The inclusion of these compounds present in plant extracts enables the diminution of metallic ions, culminating in the creation of precise NPs [59].

2.1 Synthesis of CoNPs using Plant's different parts

2.1.1 Synthesis of CoNPs from Leaves

In the search to develop a green, efficient method for synthesizing CoNPs, J.K. Sharma and co-workers used the leaves of *Calotropis gigantea*. In order to prepare the extract from the leaves, 100 g of washed leaves were taken and boiled into 200 mL of deionized water. The resulting mixture was subsequently subjected to filtration using a 0.2 µm membrane filter to eliminate fibrous impurities. A fraction of the strained foliage extract (100 mL) was subjected to heating within a temperature interval spanning (60-80) °C employing a stirrer-heater apparatus. With continuous stirring, 10 g of Cobalt Nitrate Hexahydrate ($\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$) was dissolved within the foliage extract. It was boiled for several minutes, condensed into a deep brown paste, and then kept in an oven at 400°C for 2 hours before being transported to a ceramic crucible, where it was subjected to heat treatment. Consequently, CoNPs with an average dimension of 50 nm were generated. The composition and structure of nanomaterials were interpreted using Field Emission Scanning Electron Microscopy (FE-SEM). This examination unveiled the presence of NPs having a spherical crystalline structure. They further explored the electrocatalytic activity by measuring the cyclic voltammetry in a three-electrode system, corresponding to I_2/I^{3-} and I^{3-}/I^- reactions, with increasing cathodic and anodic currents at varying scan rates. This showed their potential as effective catalysts for the iodide couple, holding significance for applications like dye-sensitized solar cells (DSSCs) involving electron injection and I^{3-} ion reduction [60]. This approach provides an affordable and eco-friendly synthesis method that can be readily scaled up for mass production. Notably, it avoids using high pressure, energy, elevated temperatures, and harmful chemicals commonly associated with alternative methods.

Muhammad Saeed and co-workers proposed another environmentally friendly method for producing CoNPs involving the *Helianthus annuus* leaf extract. To obtain the leaf extract, freshly picked leaves were gathered and dried in a shaded area. Around 15 g of the dried leaves were rinsed with and boiled with distilled water for 3 hours. Once the mixture had cooled down, the solution was filtered, separating the leaves from the liquid component. The resultant filtrate, measuring 50 mL, was then obtained and designated as the leaf extract. To commence the synthesis process, the leaf extract was gradually introduced drop by drop into a solution containing 0.5M Cobalt Nitrate ($\text{Co}(\text{NO}_3)_2$) while maintaining agitation. As the reaction mixture was stirred, CoNPs formed through precipitation. The resulting paste was washed with ethanol, followed by water, and dried at 100°C for 12 hours. Subsequently, dried powder was calcinated at 500°C for 3 hours, producing the desired NPs. The synthesized NPs were characterized with the help of different methods like X-ray diffraction (XRD), Scanning Electron Microscope (SEM), and many more. The structures of the fabricated particles were investigated employing SEM, which revealed that particles have plate-like morphology. Additionally, these tiny particles showed impressive photocatalytic properties, as seen in their capability to break down methyl orange dye. When a 100 mg/L (50 mL) solution of methyl orange was treated with 0.1g of cobalt and silver-CoNPs as catalysts, a degradation of 53% and 87% was achieved after a reaction time of 120 minutes, respectively. [61] This method offers a straightforward and

cost-effective approach with environmental friendliness, making it applicable for synthesizing various metal-metal oxide NPs materials.

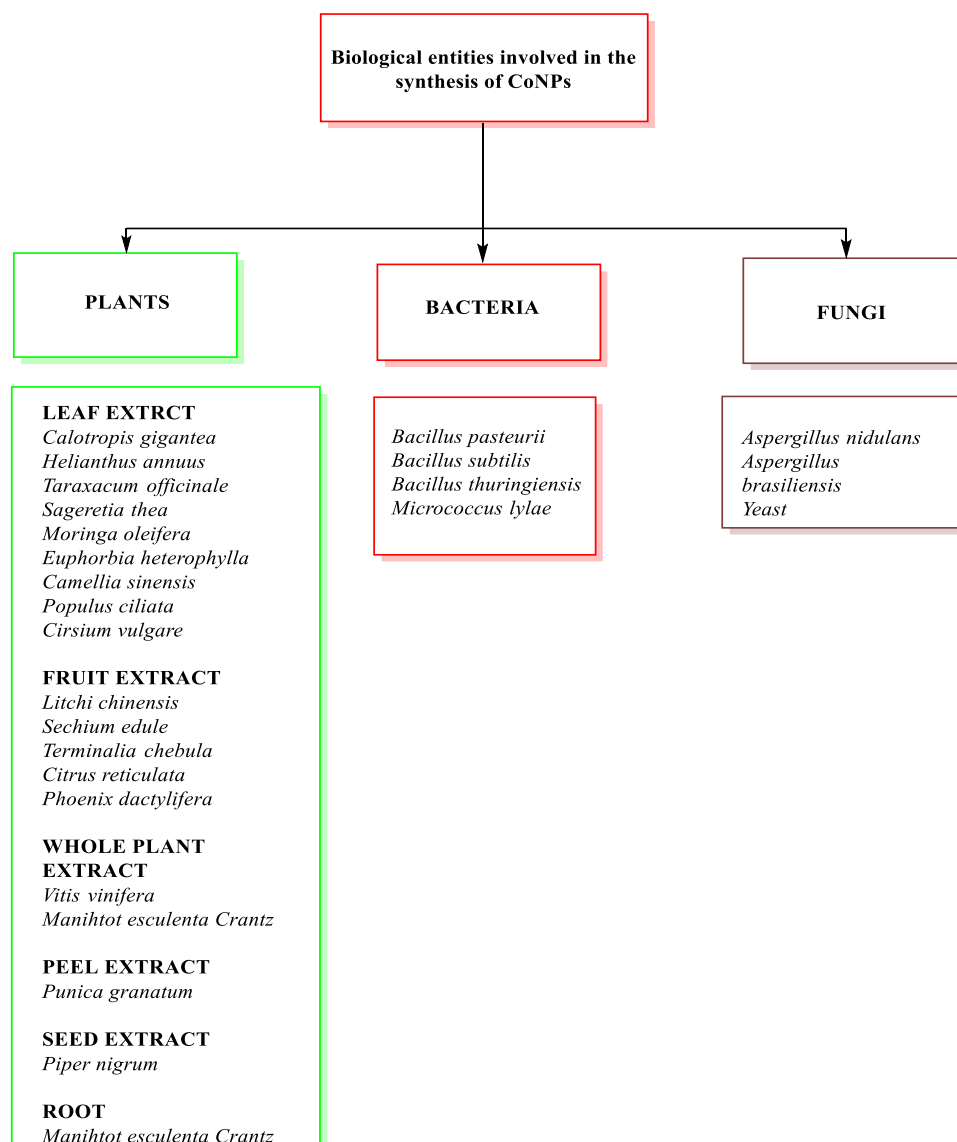


Figure 1. Biological entities involved in the synthesis of CoNPs.

Tahir Rasheed and co-workers developed an effective method using the leaves extract of *Taraxacum officinale* to synthesize CoNPs. First, they ensured cleanliness by washing the fresh leaves multiple times with warm water to prevent contamination. Then, the cleaned leaves were dried at around 28°C and ground into fine powder using an electric blender. The resulting powder was sifted to remove unwanted plant debris. The powdered *T. officinale* leaves were stored in airtight plastic bags for subsequent use in extract preparation. In the extract preparation process, 1 g of *T. officinale* leaves powder was soaked in 100 mL deionized water at 28 °C for 30 minutes. The mixture was then processed using a rotary evaporator at 60°C. The concentrated liquid was lyophilized to obtain a pure extract, which was stored at 4°C for making CoNPs. The process of CoNPs synthesis was optimized using various parameters. Initially, 1 gram of CoSO₄ was mixed with 50 mL of deionized water and combined with an equal amount of *T. officinale* leaves extract. This mixture, with a stabilizer agent, Tetrabutylammonium bromide (TBAB), for 30 minutes was gently stirred at room temperature. After that CoNPs were washed with water and acetone to eliminate excess and unreacted chemicals. These NPs were purified through

centrifugation, water washing, vacuum drying, and further used for characterization. UV-Vis Spectroscopy (UV-VIs) was performed to confirm the formation of NPs. SEM and Transmission electron microscopy (TEM) were used to examine the surface morphology of the CoNPs. They were discovered to be spherical and to range in size from 50 to 100 nm on average. These CoNPs also showed catalytic activity against the synthetic dyes methyl orange and direct yellow-142. This suggests that they have the potential to degrade harmful azo dyes effectively [62]. The successful degradation of these dyes also indicates that CoNPs could help handle other emerging contaminants.

Ali Talha Khalil and his companions reported a green method to synthesize CoNPs. They obtained leaf extracts of *Sageretia thea*, a 30 g plant's powdered material, mixed with 200 ml of deionized water. The mixture was then heated for an hour on a magnetic stirring hot plate to roughly 80°C. Following the heating procedure, the solution was filtered four times using Whatman filter paper to eliminate any solid remaining waste. And then, to the 100 ml filtered extract, 6 g of Cobalt Acetate (Co(CH₃COO)₂) was added, causing a

decrease in pH from 5.7 to 4.5. The solution was heated with gentle stirring at around 60°C for 2 hours. For 10 minutes, the solution underwent centrifugation at a speed of 10,000 rpm to gather the solid pellet after the solution had reached room temperature. The compressed substance underwent a comprehensive purification procedure, being washed three times with purified water, followed by calcination at 100°C for 2 hours. The desiccated mass was annealed in an exposed environment at 500°C, producing CoNPs, characterized by their exceptional crystallinity and purity. The CoNPs that were synthesized underwent a comprehensive characterization employing an array of analytical methodologies. XRD was used to determine their structure and calculate the particle size using the Scherer equation. Advanced SEM imaging techniques were used to study the particles' morphology, shape, and distribution. Furthermore, Selected Area Electron Diffraction (SAED) and Energy Dispersive X-ray Spectroscopy (EDX) analysis were employed to examine their characteristics and composition further. The NPs exhibited an average size of 20.3 nm. They demonstrated antibacterial activity against both gram-negative strains (*Pseudomonas aeruginosa*, *Klebsiella pneumonia*, and *Escherichia coli*) and gram-positive strains (*Staphylococcus epidermis*, *Staphylococcus aureus* and *Bacillus subtilis*). Moreover, the NPs displayed antioxidant properties. For DPPH radical scavenging activity, the highest inhibition (57%) was observed at 200 µg/ml. Lower concentrations resulted in a reduction in scavenging capacity. Similar patterns were seen for both total reducing power and total antioxidant activity. At 200 µg/ml, the bioinspired CoNPs showed the highest total reducing power (19.8 µg AAE/mg) and total antioxidant capacity (23.6 µg AAE/mg). Overall, these NPs exhibited moderate to good antioxidant potential [63]. This eco-friendly green synthesis method provides a practical and alternative approach for biosynthesizing CoNPs, which can be utilized in various biological applications.

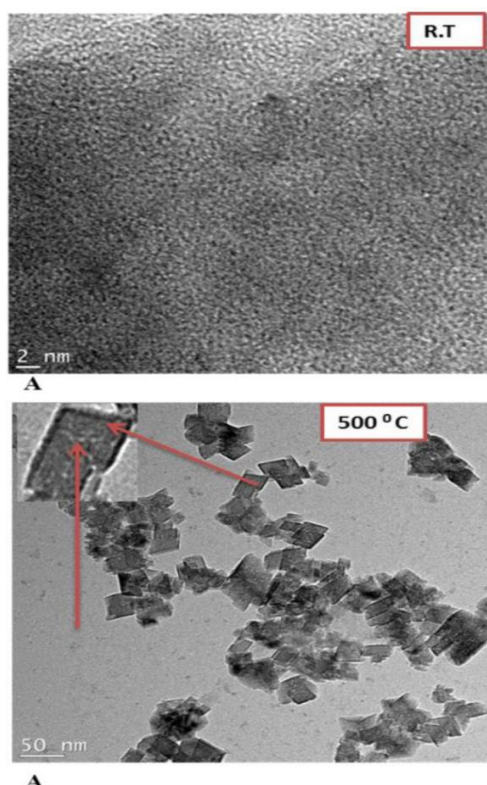


Fig. 2. (A) HRTEM images of nanoparticles synthesized using extracts from *Moringa oleifera* leaves [64]. Copyright © AIP Publishing.

Nolubabalo Matinise and the group developed another highly effective method for synthesizing CoNPs by utilizing extracts from the leaves of *Moringa oleifera*. The procedure started by submerging 30 g of purified and dried *Moringa oleifera* leaves in 300 ml of boiled demineralized water. The mixture was subjected to magnetic stirring at approximately 50°C for around 1 hour and 45 minutes. Subsequently, the mixture was cooled to ambient temperature and filtered using a nylon mesh and a Millipore filter to achieve filtration. The resulting extract obtained from *Moringa oleifera* was then securely stored in a refrigerator for further analysis. 5 g of $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ and 50 ml of extract was dissolved under magnetic stirring for 1 hour to prepare the sample. The solution was kept in a standard oven in the dark at 100°C for 18 hours for drying. Then, multiple rinses with deionized water were performed to remove unnecessary materials from the extract. In the final step, the sample again underwent heating at 500°C for 2 hours, which resulted in CoNPs. Various characterization techniques were employed to analyze the synthesized CoNPs, like EDX, XRD High-Resolution Transmission Electron Microscopy (HR-TEM) (Fig. 2), and many more. After analysis, the CoNPs that were produced showed a symmetrical shape, with sizes ranging from 20-50 nm. Tests were carried out to assess their electrochemical performance, including cyclic voltammetry, electrochemical impedance spectroscopy, and galvanostatic charge-discharge measurements [64]. These green chemistry routes' advantages include cost-effectiveness, the absence of extra chemicals, reliability, and minimal waste generation, making them environmentally friendly and straightforward.

Nur Oktri Mulya Dewi and her team introduced an innovative eco-friendly approach for crafting CoNPs using *Euphorbia heterophylla* L. leaves. They began by washing the leaves and allowing them to air dry at room temperature, and then the leaves were crushed into a fine powder. Using methanol, this powder underwent a maceration procedure in which the mixture was agitated daily for a week. Hexane (1:1) (weight-to-volume ratio) was then used to separate the solution into methanol and hexane fractions. The leaves of *Euphorbia heterophylla* L. were turned into an aqueous extract using concentrated methanol and distilled water. Drops of this extract were gently added to a $\text{Co}(\text{NO}_3)_2$ solution, and the mixture was agitated at 80°C for two hours. After that, CoNPs were produced by calcining the mixture at 550°C for four hours. These synthesized CoNPs underwent several characterization processes. Functional groups that were present were identified using FT-IR spectrometry. To examine the NPs absorption spectra, a UV-VIS spectrophotometer was used. The distribution of particle sizes was determined using a Particle Size Analyzer. Through TEM, it was established that the NPs were spherical, with an average size of 69.75 nm. To assess their effectiveness in catalyzing reactions under light, 3 mg of the CoNPs were introduced into a solution of methylene blue (with a concentration of 2×10^{-5} M) in a volume of 25 mL. The mixture was then exposed to visible light for 3 hours. The NPs exhibited a photocatalytic capability, resulting in a 63.105% degradation of methylene blue under visible light irradiation for the specified duration [65]. This method stands out for its environmentally friendly, cost-effective, and efficient nature.

C.T. Anuradha and her team proposed another environmentally friendly technique for crafting CoNPs using *Camellia sinensis* leaf extract. They began by meticulously cleaning healthy *Camellia sinensis* leaves with double-distilled water multiple times. Subsequently, the leaves were crushed into a powder after being air-dried at room temperature. 100 mL of deionized water and 10 g of this powdered leaf material

were combined and swirled magnetically for an hour at 70°C. Whatman's No.1 filter paper was used to filter the resultant aqueous leaf extract, and the clear solution was collected and stored in a spick and span container. Instead of utilizing inorganic or organic reducing agents, 50 mL of the aqueous leaf extract was evenly mixed with 100 mL of a transparent solution containing Cobalt Chloride Hexahydrate ($\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$) while agitating at a speed of 1000 rpm. The mixture was heated to 90°C until a stable solution was produced. The fluid hardened and became gel-like as the temperature rose from 130 to 150°C. The plant components in the leaf extract served as the reducing agent in a redox-active process that led to the natural breakdown of this gel. The resulting precursor was ground with a mortar and pestle into a fine powder. The obtained fine powder was subjected to annealing at various temperatures, i.e. 200°C, 400°C, 600°C, 800°C, and room temperature for 120 minutes. This facilitated the successful creation of CoNPs using the *Camellia sinensis* leaf extract at distinct calcination temperatures. The researchers utilized FE-SEM, XRD, and HR-TEM techniques to examine the NPs' crystalline structure, surface characteristics, functional groups, and grain size. It was observed that the crystalline behavior improved with higher calcination temperatures, with an average grain size of 39.13 nm reported at 800°C. Moreover, the electrochemical performance of these bio-synthesized CoNPs demonstrated outstanding supercapacitance capabilities. This was attributed to their rapid electrolyte ion dispersal within the Co_3O_4 electrode, resulting in swift charging and discharging. This verified the suitability of the bio-synthesized cobalt nanomaterial for high-performance supercapacitor applications [66].

Muhammad Hafeez and his collaborators introduced a highly beneficial eco-friendly approach using extracts from *Populus ciliata* leaves for synthesizing CoNPs. The process began by washing the leaves with tap water and distilled water. After air-drying the leaves at room temperature for 24 hours, they were finely chopped using a mechanical blender. 100 ml of distilled water and 100 grams of these chopped leaves were put into a 250 ml glass beaker. The mixture was warmed until it was boiling. After 2 hours of heating, the solution's color transformed from colorless to light brown. The solution was allowed to cool down to room temperature, then filtered and stored in a refrigerator for later use. To synthesize CoNPs, they used $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ as the starting material. A solution of this salt was prepared with a concentration of 1 mmol by dissolving 2.91 g of it in 100 ml of distilled water. They combined 30 ml of the cobalt salt solution in a glass beaker with 20 ml of the previously prepared leaf extract. Then, the mixture was heated to 80°C and maintained at that level for three hours. The emergence of a color change, transitioning from a light brown shade to a dark brown color, indicated the successful creation of CoNPs. After allowing the solution to cool down to room temperature, it was centrifuged at 15,000 rpm for 15 minutes. The resulting supernatant was removed, leaving behind a residue of NPs, which were then dried at 60°C in an oven. The verification of the successful synthesis of CoNPs was carried out through powder XRD. The size of the particles was estimated using the Scherrer formula, revealing a range of 40 to 50 nm. Additionally, TEM was conducted to investigate the structural features of the CoNPs, revealing a square-like shape. Furthermore, these synthesized CoNPs exhibited antibacterial properties against both gram-positive (*Staphylococcus aureus*, *Staphylococcus epidermis*, and *Bacillus subtilis*) and gram-negative (*Klebsiella pneumonia*, *Pseudomonas aeruginosa*, and *Escherichia coli*) bacterial pathogens. The researchers noted that the antibacterial effectiveness of these NPs increased

with higher concentrations [67]. This innovative method offers a cost-effective and environmentally friendly means of producing CoNPs.

Maryam Fallahi and her research team introduced a remarkably effective eco-friendly approach for crafting CoNPs utilizing the aqueous leaf extract of the *Cirsium vulgare* plant. Their procedure commenced by drying the leaves in a laboratory oven at a temperature of 50°C and subsequently grinding them into a powdered form. For the *Cirsium vulgare* extract, 60 g of this powdered material was mixed with 1500 mL of ethanol and left to rest over five consecutive nights. Following this, the solution was filtered to eliminate any precipitates, resulting in an extract ready for synthesis. For the actual nanoparticle synthesis, a solution of aqueous Cobalt chloride (CoCl_2) (250 mL, 0.1 M) was combined with the *Cirsium vulgare* extract (250 mL, 40 g/L) under vigorous stirring for 2 hours. The resulting mixture was allowed to sit overnight and subsequently underwent centrifugation. The precursor material obtained was then subjected to calcination in a furnace at a temperature of 400°C for 2 hours. This process led to the formation of a solid mass in black color, which was identified as CoNPs. The sizes of these CoNPs were determined through XRD, revealing a particle size of approximately 20 nm. A constant phase element of CoNPs was also prepared using a straightforward method, highlighting their electrochemical properties. This innovative approach showcases a significant step towards eco-friendly nanomaterial synthesis and underscores the potential of CoNPs for various applications [68].

2.1.2 Synthesis of CoNPs from Fruits

Damian C. Onwudiwe and co-workers proposed another method using *Litchi chinensis* (Litchi fruits). The peel of the fruits was wholly cleansed, dehydrated, and crushed into a fine powder. Afterward, 5 g of the powdered peel was boiled in 200 mL of purified water with ongoing agitation for 2 hours. The resulting pink solution containing the desired phytochemicals was collected and utilized to synthesize NPs. In one approach, 100 mL of the litchi extract was combined with a solution of 0.02 M $\text{Co}(\text{CH}_3\text{COO})_2$ and heated at 80 °C. Then, it was boiled for 2 hours, and a dark green color appeared, indicating the formation of NPs. In an alternative method, 4 g $\text{Co}(\text{CH}_3\text{COO})_2$ was dissolved in 50 mL of the litchi extract. Then, the mixture was subjected to ultrasonication and microwave irradiation for 6 minutes, forming NPs. The rod-like shape fabricated NPs were validated through XRD, while FT-IR spectroscopy was utilized to examine the functional biomolecules in the fruit peel extract. With the help of TEM, the inner structure of the NPs was investigated, and the outer structure was analyzed using scanning electron microscopy. The outcomes of this study testified to the practical fabrication and characterization of CoNPs utilizing Litchi fruit peel extract as a biogenic reducing agent, which verified their potential applications in diverse domains. The method used resulted in the formation of rod-shaped NPs with a size range of 26 to 40 nm [69].

Raj Kumar Das and his co-workers showed an alternative green method involving the utilization of fruit extract from *Sechium edule* (mature squash fruits). For the bio-extract, 75 g of fruit pieces measuring (5 mm × 4 mm × 2.5 mm) were boiled in 350 mL of deionized water at 85-90°C for 12 hours with stirring. Following filtration, a bio-extract solution with a pH of 5.63 and a volume of 390 mL was obtained. The process began by mixing at 300 rpm of 50 mM $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ solution with a bio-extract in a 1:1 volume ratio at a pH of 5.16 for 48 hours at a temperature of 65-70°C. The pH was then adjusted

to 11 using 2 M NaOH. Afterward, the grey-brown residue was collected by centrifugation at 4000 rpm for 5 minutes. After this, the residue was dispersed in a solution of deionized water and ethanol (30:70 %) and subjected to 10 minutes of sonication at 40 kHz. Once the residue was collected through centrifugation, the rinsing process was repeated three times to remove uncoordinated biomolecules. Following these steps, the residue was dried at 95°C using a hot air oven. Subsequently, it was calcined at temperatures of 500°C and 700°C for 6 and 12 hours in a muffle furnace. This led to the formation of CoNPs, and for the characterization, XRD, UV-vis, FT-IR, TGA, SEM, and TEM were performed, which resulted in an average diameter size of 31.79nm and irregular shape of synthesized CoNPs. To explore the electrocatalytic properties, a Graphite-Co₃O₄ electrode was prepared, which showed great sensitivity for detecting H₂O₂, as revealed by the lower overpotential value of 1.843 V [70].

Thomas Nesakumar Jebakumar Immanuel Edison and his colleagues utilized *Terminalia chebula* fruit extracts to synthesize CoNPs. The dried and ground *T. chebula* fruit (500 mg) was combined with 50 mg Cobalt (II) acetate tetrahydrate (Co(CH₃COO)₂·4H₂O), meticulously grounded using a mortar and pestle, then heated at 450°C in a silica crucible for four hours in a Muffle furnace. The resulting method successfully produced CoNPs. Various analytical techniques like Attenuated Total Reflection with FTIR, XRD, TEM, and SEM with Energy Dispersive Spectroscopy were applied to comprehend their characteristics. ATR-FTIR indicated that phytoconstituents underwent carbonization, corroborating CoNP's presence. XRD patterns showcased their high crystallinity and carbon support. Microscopic images revealed that the particle size was between 15-25 nm with a somewhat

distorted spherical shape. Moreover, for the supercapacitor performance, carbon-CoNPs were prepared in which OH⁻ ions were penetrating and responsible for the high conductivity [71].

Rishabh Srivastava and his colleagues utilized *Citrus reticulata* fruit peels as a natural reducing agent for environmentally friendly synthesis. The process commenced with washing and drying orange fruits at ambient temperature. The collected orange peels were peeled, dried in a 60°C oven overnight, and ground into a fine powder. Two grams of this powdered peel were mixed with 50 mL of deionized water, stirred for 3 hours at room temperature, and then gently warmed in a water container at 60°C for 60 minutes. The resulting mixture was filtered to obtain the essence. Subsequently, 2 g of Co(NO₃)₂ was added to 42.5 mL of the peel extract and stirred at room temperature for an hour. The mixture was then transferred to a water bath at 60°C and dried overnight. The resulting CoNPs underwent further transformation through calcination at 400°C. These NPs were comprehensively characterized using various analytical techniques, including Raman spectroscopy, TGA, Vibrating sample magnetometer, XRD, TEM, and Atomic force microscopy (Fig. 3). In this approach, the NPs displayed sizes ranging from 14.2 to 22.7 nm and exhibited an octahedral shape. Electrochemical and Supercapacitor properties were assessed using cyclic voltammetry, galvanostatic charge-discharge, and electrochemical impedance spectroscopy. The stability of synthesized NPs was also evaluated to identify the optimal outcome for specific capacitance in a 3M KOH solution [72]. This method showcased superior coulombic efficiency, energy, and power density performance, demonstrating the potential of plant-synthesized NPs.

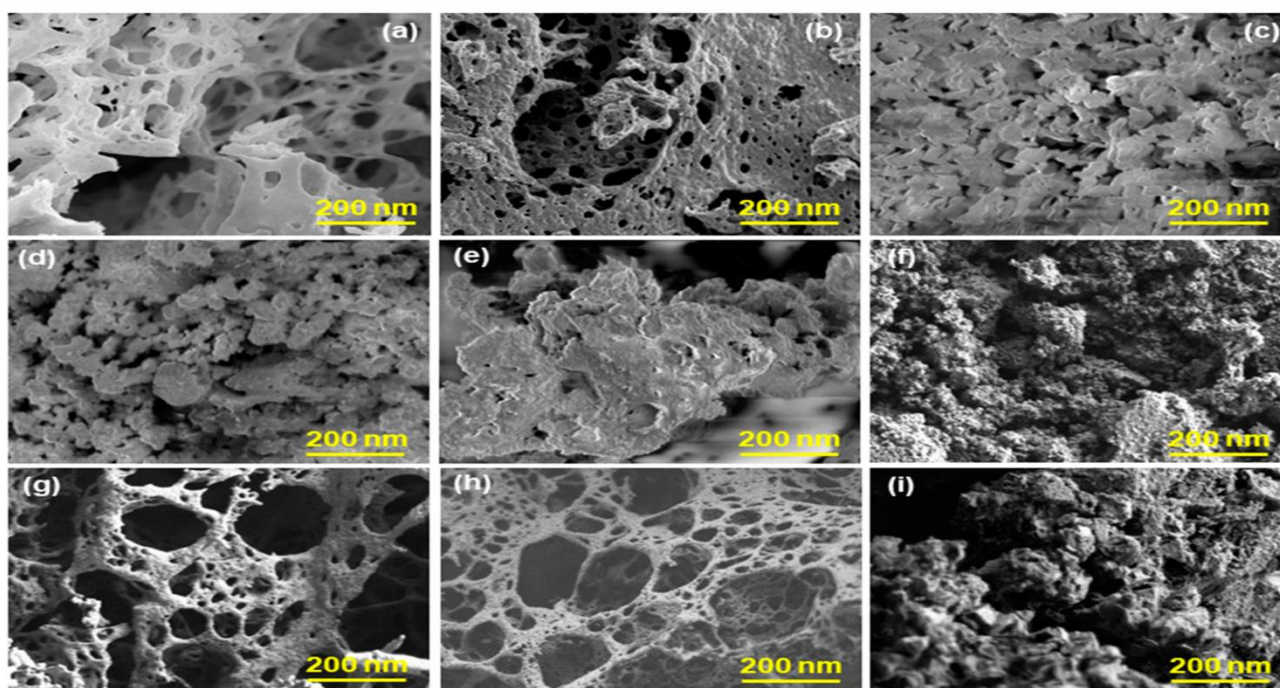


Fig. 3. The SEM images of the prepared nanoparticles synthesized using extracts from *Citrus reticulata* fruit peels [72]. Copyright © Nanomaterials.

Devi Rajeswari and her team utilized a green approach employing fruit extracts from *Phoenix dactylifera* to synthesize CoNPs successfully. This innovative method involved the utilization of fruit extract for the creation of these NPs. The resultant CoNPs were subjected to a comprehensive characterization process involving various techniques, like

UV-visible absorption spectroscopy, to analyze the NPs, revealing a distinct peak at 530 nm in the absorption spectrum. Fourier Transform Infrared Spectroscopy was used to pin point functional groups, and XRD was employed to determine the NPs crystalline makeup. SEM provided insights into the NPs physical structure, showcasing their spherical

shape with an average size of around 80 nm. Additionally, particle size and zeta potential measurements were carried out. The cobalt oxide NPs displayed a zeta potential value of approximately -30.8 mV. Furthermore, the antimicrobial properties of the synthesized NPs were examined across varying concentrations. Notably, the NPs displayed robust antibacterial efficacy against gram-positive bacteria (*Bacillus et al. aureus*) and gram-negative bacteria (*Klebsiella et al.*). Furthermore, they showcased notable effectiveness in inhibiting the growth of the fungus *Aspergillus niger*. The research also delved into assessing the photocatalytic capabilities of the synthesized cobalt oxide NPs. This involved monitoring the reduction in the concentration of Congo red dye under the influence of solar radiation. The results revealed a significant degradation of 92.45% after 70 minutes, highlighting the NPs notable photocatalytic potential [73].

2.1.3 Synthesis of CoNPs from Whole Plant extract

Kombaiah K and group reported another method involving *Vitis vinifera* whole plant extract. In this method, a stoichiometric amount of $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ and glycine were added to 50ml of deionized water and subjected to stirring for 1 hour to ensure homogeneity. The resulting solution was then heated to 250°C on a hot plate for 15 minutes, undergoing a combustion reaction that formed an active mixture. This mixture appeared as a black precipitate, which was subsequently separated through centrifugation, rinsed with purified water, and dried at a temperature of 100°C. Further annealing of the dried precipitate was conducted at 300°C for 2 hours under an air atmosphere, forming CoNPs. XRD, FTIR, Raman spectrophotometry, HR-TEM, and UV-visible diffuse reflectance spectrophotometry were performed on the synthesized CoNPs. This comprehensive investigation revealed that the NPs had dimensions ranging from 10 to 20 nm and exhibited a rod-like shape, along with possessing photocatalytic activities, which were investigated for the degradation of textile dyeing wastewater and had antibacterial properties towards both Gram-positive and Gram-negative bacteria [74].

Tayyaba Shahzadi and her co-workers successfully synthesized NPs from the whole plant extract of *C. argentea*. Initially, plant material was carefully cleaned and shade-dried, followed by grinding into a powdered form. For the extract, 50g of the whole Plant powdered was added to 300 mL of 30% methanol solution in a 500 mL flask. The final mixture was heated at 70°C with intense stirring for 30 minutes, and subsequent separation was carried out. For the synthesis of CoNPs 15 mL of the prepared plant extract was slowly added dropwise to a 0.003M aqueous solution of CoCl_2 while maintaining a stirring at 80°C for 30 minutes. A noticeable color change occurred in the reaction mixture, indicating the successful formation of CoNPs. Subsequently, the solution containing the synthesized NPs was centrifuged at 7000 rpm for 40 minutes to separate them from the remaining components. Characterization of the synthesized CoNPs involved the application of various analytical techniques like FT-IR, XRD, EDX, and FE-SEM, which were used to examine the morphology of the NPs in depth. By using this complete range of characterization methods, the CoNPs measured the average size of 27.42 nm and possessing antioxidant activity against 2,2-diphenyl-1-picrylhydrazyl radical and antibacterial properties were tested separately against Gram-positive bacteria (*Bacillus subtilis*) and Gram-negative bacteria (*Escherichia coli*) [75]. This green method offers enhanced convenience by eliminating the need for cell cultures, ensuring ease of handling, and delivering high nanoparticle yields

without generating harmful byproducts.

2.1.4 Synthesis of CoNPs from Peel

Ismat Bibi and group used the peels of *Punica granatum*, commonly known as pomegranate. In this process, the peels were carefully sliced and washed with ultrapure water to remove the impurities. After this, a mixture of 20 g peels with 150 ml of water was homogenized in an electrical grinder. Then, the resulting mixture was heated at 75°C while continuously stirring. Subsequently, the mixture was cooled, and the liquid was separated by filtration. The filtrate, displaying a brown color, served as the basis for synthesizing CoNPs. For the synthesis, the peel extract was mixed with a solution of $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, and the resultant mixture was heated at 70°C until precipitates began to appear. The temperature was subsequently decreased to 60°C, and the solution was maintained at 60°C for 90 minutes to allow additional reaction. After overnight incubation at room temperature, the mixture was centrifuged at 14000 rpm for 10 min, and the resulting precipitates were thoroughly washed with ethanol and water to eliminate impurities. The dried precipitates were subsequently ground and subjected to comprehensive characterization with the help of XRD, EDXR, SEM, FT-IR, and AFM, resulting in the particle size being 40-80 nm, spherical, and having photocatalytic activity. The photocatalytic activity was evaluated by degrading Remazol Brilliant Orange (RBO) 3R dye under solar light irradiation, where degradation of 78.45% was achieved within 50 minutes of irradiation time using 0.5 g of CoNPs [76].

2.1.5 Synthesis of CoNPs from Seed

P. Saravanakumar and their companion utilized the *Piper nigrum*, commonly known as black pepper's seed extract, for a green approach to synthesizing CoNPs. For the extract, 10g seeds were finely ground into a powder and boiled with 100 mL of distilled water. After this, the mixture was filtered using Whatman No.41 filter paper, collected, and stored in a refrigerator. For the CoNPs synthesis, 100 mL of the seed extract with a solution of 0.1N CoCl_2 followed by stirring for 30 minutes. Then, the mixture was subjected to reflux at an elevated temperature for 2 hours. As a result of this process, brown-colored NPs are obtained, which are subsequently filtered and prepared for characterization and potential applications. Using XRD, FTIR, and UV-VIs, the size of NPs was found to be 30-60 nm, spongy triangular. The degradation efficiency of pure crystal violet dye with or without UV irradiation exposure was checked for photocatalytic properties. This resulted in the dye solution not being easily degraded [77]. This method proves valuable for removing organic dyes and finding applications in environmental remediation and water purification processes.

2.1.6 Synthesis of CoNPs from Root

E.U. Ikhuria and colleagues utilized an alternative approach involving *Manihot esculenta* Crantz roots. The tuberous root parenchyma underwent a series of processing steps, including peeling, washing, grating, and dewatering. The resulting extract was centrifuged to eliminate starch, and the liquid above was subsequently preserved at 4°C. In a standard trial, a solution containing 0.02 mol CoCl_2 was mixed with 30 mL of the extract from *Manihot Esculenta* Crantz for stabilization. After allowing the combination to rest for 24 hours, a precipitate was isolated and dehydrated in a vacuum oven. The dehydrated powder was further heated at 500°C for 2 hours to encourage the creation of CoNPs. The

characterization of the synthesized powders was examined through various methods like HR-SEM, HR-TEM, EDS, and FT-IR. Which resulted in the CoNPs having a distinctive prism-like anchored octahedron shape. These NPs exhibited antiferromagnetic properties and possessed band gaps of 2.86 eV and 2.54 eV, respectively [78]. This method is optimistic for widely adopting this simple and environmentally friendly green approach in synthesizing CoNPs.

It has been observed for the synthesis of CoNPs, different parts of the Plant have been used, like leaf, fruit, whole Plant, peel, and seed mentioned in Table 1. The table presents a comprehensive overview of various plant extracts using different parts and their corresponding NPs in terms of size, shape, and applications.

Table 1. Parts of Plants Used for the Synthesis of CoNPs along with Applications.

S.No	Plant Scientific Name	Part	Cobalt Salt	NPs Size (nm)	Shape	Application
1	<i>Calotropis gigantea</i>	Leaf extract	$\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$	50	Spherical	Catalytic activity [60]
2	<i>Helianthus annuus</i>	Leaf extract	$\text{Co}(\text{NO}_3)_2$	NA	Plate	Photocatalytic activity [61]
3	<i>Taraxacum officinale</i>	Leaf extract	CoSO_4	50-100	Spherical	Catalytic activity [62]
4	<i>Sageretia thea</i>	Leaf extract	$\text{Co}(\text{CH}_3\text{COO})_2$	20.03	Cubic	Antibacterial, Antioxidant [63]
5	<i>Moringa oleifera</i>	Leaf extract	$\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$	20-50	Triangular	Electrochemical properties [64]
6	<i>Euphorbia heterophylla</i> L.	Leaf extract	$\text{Co}(\text{NO}_3)_2$	69.75	Spherical	Photocatalytic activity [65]
7	<i>Camellia sinensis</i>	Leaf extract	$\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$	39.13	Quasi-rectangular	Electrochemical properties [66]
8	<i>Populus ciliata</i>	Leaf extract	$\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$	15-35	Square shape	Antibacterial [67]
9	<i>Cirsium vulgare</i>	Leaf extract	CoCl_2	20	Semi-spherical	Electrochemical properties [68]
10	<i>Litchi chinensis</i>	Fruits extract	$\text{Co}(\text{CH}_3\text{COO})_2$	26–40	Rod-like	Supercapacitors [69]
11	<i>Secchium edule</i>	Fruit extract	$\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$	31.79	Irregular	Electrocatalytic properties [70]
12	<i>Terminalia chebula</i>	Fruit extract	$\text{Co}(\text{CH}_3\text{COO})_2 \cdot 4\text{H}_2\text{O}$	15-25	Spherical	Pseudocapacitance activity [71]
13	<i>Citrus reticulata</i>	Fruit extract	$\text{Co}(\text{NO}_3)_2$	14.2–22.7	Octahedral	Electrochemical properties, Supercapacitor [72]
14	<i>Phoenix dactylifera</i>	Fruit extract	$\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$	80	Spherical	Antibacterial, Photocatalytic, Antimicrobial activity [73]
15	<i>Vitis vinifera</i>	Whole plant extract	$\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$	10-20	Rod shape	Photocatalytic, Antibacterial activities [74]
16	<i>Celosia argentea</i>	Whole plant extract	CoCl_2	27.42	Spherical	Antioxidant, Antibacterial [75]
17	<i>Punica granatum</i>	Peel extract	$\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$	40-80	Spherical	Photocatalytic activity [76]
18	<i>Piper nigrum</i>	Seed extract	CoCl_2	30-60	Spongy triangular	Photocatalyst [77]
19	<i>Manihot esculenta</i> Crantz	Root extract	CoCl_2	N/A	Prism - like anchored octahedron	Magnetic and Optical properties [78]

It is clearly evident that the shape of nanoparticle is independent of the choice of cobalt salt and plant/ plant part taken. Only a selective domain of biological applications is still explored, i.e. antioxidant, antibacterial and antimicrobial. They can be further utilized to check their significance against other biological applications such as antitubercular, anticancer, antiproliferative and many more. Their catalytic benefits can be incorporated in organic synthesis to enhance the process.

2.2 Synthesis of CoNPs using Bacteria

For the green synthesis of CoNPs, some bacteria were used, as mentioned in Table 2. Diverse bacterial strains and their respective biosynthesized nanoparticles (NPs), shedding

light on their unique sizes, shapes, and applications can be observed here. For instance, *Bacillus pasteurii* produces irregularly shaped NPs ranging from 10 to 31 nm, positioning itself as a contender for supercapacitor applications [79]. *Bacillus subtilis*, on the other hand, yields hollow rod-shaped NPs with a size of 6.6 nm, showcasing potential in supercapacitor technology [80]. *Bacillus thuringiensis* exhibits face cubic NPs measuring 85.3 nm, demonstrating larvicidal activities [81]. Lastly, *Micrococcus Lyle* synthesizes flower-like NPs of 8 nm, showcasing versatility in antioxidant, antifungal, and antimicrobial applications [82]. This compilation provides valuable insights into the diverse applications of bacterial strain-synthesized NPs, ranging from energy storage to environmental and biomedical applications.

Table 2. Synthesis of CoNPs using bacteria.

S. No	Bacterial Strain	Nps Size (nm)	Cobalt Salt	Shape of CoNPs	Application
1	<i>Bacillus pasteurii</i>	10–31	$\text{Co}(\text{NO}_3)_2$	Irregular	Supercapacitor [79]
2	<i>Bacillus subtilis</i>	6.6	$\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$	Hollow rod	Supercapacitor [80]
3	<i>Bacillus thuringiensis</i>	85.3	$\text{Co}(\text{CH}_3\text{COO})_2$	Face cubic	Larvicidal Activities [81]
4	<i>Micrococcus Lyle</i>	8	$\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$	Globular	Antioxidant, Antifungal, Antimicrobial [82]

Chun-Mei Hsu and the group reported a green method using *Bacillus pasteurii*, a non-pathogenic gram-positive bacterium known for its high urease activity, to conduct a microbial-induced precipitation experiment. The bacterium was cultivated in a medium of 20g/L yeast extract, 10g/L ammonium sulfate, and 130 mM Tris-Base. The growth of the bacteria was monitored with the help of spectrophotometric and colony-forming unit methods, and a bacterial concentration of 1.2×10^7 cells/mL was selected for the microbial-induced precipitation experiment. In the synthesis process, NPs were formed by reacting urea, *B. pasteurii*, and 30mL Cobalt (II) nitrate $\text{Co}(\text{NO}_3)_2$ in a 50mL centrifugal tube. Bacterial broth and $\text{Co}(\text{NO}_3)_2$ concentrations were varied to standardize the synthesis procedure. After an incubation period, the precipitate was collected through centrifugation, washed with ethanol to remove impurities, and dried. The resulting material was referred to as a "hybrid bio-cobalt compound." To obtain NPs, the hybrid compound was subjected to calcination at different temperatures, and the NPs were obtained. The synthesized NPs were evaluated using XRD, FE-SEM, and TEM, which showed that the size of CoNPs was 10-31 nm with irregular shape. For the electrochemical properties, there is an electrode system (Ni as the working electrode, an Ag/AgCl references electrode, and a platinum wire as the counter electrode) [79]. This environmentally friendly green synthesis method offers an efficient and alternative approach to biosynthesizing CoNPs, opening up possibilities for their application in diverse biological contexts.

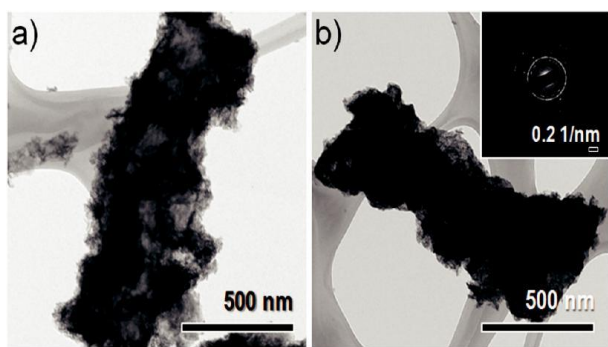


Fig. 4. TEM images of the prepared nanoparticles rods that were calcined at (a) 200 °C and (b) 300 °C and synthesized using extracts from *Bacillus subtilis* bacteria. ©Copyright © 2010 American Chemical Society.

Hyun-Woo Shim and their companion developed another eco-friendly method for CoNPs utilizing the *Bacillus subtilis* bacteria. The bacterial cells were cultured in Luria-Bertani broth supplemented with chloramphenicol at 37°C and 200 rpm. The culture was propagated and calibrated to achieve an optical density of 2.0 at a wavelength of 600nm, ensuring favorable conditions for optimal growth. To synthesize cobalt oxide nanostructures, a precursor solution containing $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ and a reducing agent, Sodium borohydride, were added to the bacterial suspension.

The mixture was stirred at 700 rpm and room temperature. After 30 minutes of stirring, the reducing agent was slowly introduced, and the mixture was further stirred for 24 hours. The resulting mixture was centrifuged after the synthesis process to separate the precipitate. It was then washed with water and acetone to remove impurities before drying at 60°C under vacuum conditions. Subsequently, the bacterial/cobalt oxide composite rods were calcined at 200°C and 300°C for 12 hours, forming hollow cobalt nanostructures. To characterize synthesized CoNPs, we used UV-visible spectroscopy, FTIR, Raman spectroscopy XRD, FE-SEM, and HR-TEM, resulting in the 6.6nm size of NPs (**Fig. 4**). The electrochemical properties were testified by making the porous Co_3O_4 hollow rods for recharging the Li-ion batteries [80]. The method presents a simple, cost-effective, environmentally friendly approach, enabling the synthesis of a range of metal-metal oxide NPs.

For an alternative approach to synthesizing CoNPs, Sampath Marimuthu and the group reported a method. In which *Bacillus thuringiensis* cells were cultivated in a suspension culture. This involved using sterile distilled water supplemented with appropriate carbon and nitrogen sources, allowing the cells to grow and develop for 36 hours. A portion of the culture was then diluted and combined with $\text{Co}(\text{CH}_3\text{COO})_2$, and the resulting mixture was incubated in a shaking incubator at 37°C for 12 hours. The emergence of a red deposition at the flask's bottom indicated the commencement of the reduction process. Following incubation at room temperature for 12 to 48 hours, distinct coalescent clusters of CoNPs with a blackish-dark-red color precipitated at the flask's bottom. To enhance the stability of the synthesized NPs, cetyltrimethylammonium bromide, a surfactant, was introduced into the solution. Subsequently, the resulting mixture was freeze-dried, allowing for further characterization. Several analytical techniques, including XRD, FTIR, FE-SEM, EDX, and TEM, were utilized to examine the synthesized CoNPs thoroughly. These characterization methods provided significant findings regarding the average size of the NPs, which measured 85.3 nm, and their cubic face shape. Additionally, larvicidal activities were observed in the synthesized NPs against *A. subpictus* and *A. aegypti*, with LC_{50} values of 3.59 mg/L and 2.87 mg/L, respectively. This research study effectively showcased the synthesis of CoNPs by harnessing the potential of *Bacillus thuringiensis* cells. It also emphasized the crucial role of surfactants in governing the stability, shape, and size of the NPs. By utilizing microbial systems, such as *Bacillus thuringiensis*, for the green synthesis of NPs, it is possible to explore sustainable and environmentally friendly methods for nanoparticle production [81].

2.3 Synthesis of CoNPs using Fungi

In order to green synthesis of CoNPs, some fungi were used, as mentioned in Table 3. The table delineates fungal species and their corresponding biosynthesized nanoparticles (NPs), offering insights into their dimensions, shapes, and applications. This compilation underscores the diverse

capabilities of fungal species in synthesizing NPs with multifaceted applications, from energy storage to

antimicrobial and surface-coating technologies.

Table 3. Synthesis of CoNPs using Fungi

S. No	Fungal Species	NPs Size (nm)	Cobalt Salt	Shape of CoNPs	Application of NPs
1	<i>Aspergillus nidulans</i>	20.29	$\text{Co}(\text{C}_5\text{H}_7\text{O}_2)_3$	Spherical	Supercapacitor, Photocatalytic activity [83]
2	<i>Aspergillus brasiliensis</i>	20–27	$\text{CoSO}_4 \cdot 7\text{H}_2\text{O}$	Quasi-spherical	Antimicrobial activity [84]
3	Yeast	24	$\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$	Hollow spheres	Antireflection, Surface coating [85]

Ajuy Sundar Vijayanandan and his group proposed a very efficient green method from *Aspergillus nidulans* fungi; the initial step involved the isolation of fungus. This was achieved by treating the samples (Leaves, stems, flowers, and fruits) of *Nothapodytes foetida* plant with a solution of 75% ethanol for 1 minute, followed by exposure to a 2.5% sodium hypochlorite solution for 3 minutes. Then, they were carefully rinsed with sterile distilled water. After this, treated samples were dried, cut into small pieces (0.5cm), and evenly distributed on sterile Polydopamine (PDA) media supplemented with chloramphenicol. Following an incubation period of 3 days at ambient temperature, subculturing was performed to obtain pure isolates, ensuring the isolation of specific fungal strains from the original samples. To evaluate the tolerance of the fungal isolates, they were exposed to varying concentrations of Cobalt Acetylacetonate ($\text{Co}(\text{C}_5\text{H}_7\text{O}_2)_3$) salt (500 ppm and 1000 ppm) on PDA plates alongside control plates without the salt solution. Isolates that demonstrated enhanced tolerance and exhibited superior colony growth compared to the control were carefully selected for subsequent nanoparticle synthesis. The growth of these isolates was meticulously monitored by measuring the diameter of their colonies and calculating the tolerance index, providing a quantitative assessment of their resilience to the $\text{Co}(\text{C}_5\text{H}_7\text{O}_2)_3$ salt. Following the selection of the suitable isolate based on tolerance studies, the synthesis of NPs was carried out. The fungal inoculum was obtained from the agar plate and introduced into a conical flask containing 100mL PDA medium. The flask was then placed in a rotary shaker at 115 rpm and incubated for three days. Subsequently, Whatmann paper No. 1 subjected the resulting solution to filtration to separate the NPs from the fungal biomass. The biomass was further washed to eliminate residual components from the growth medium. The washed mycelium was subsequently combined with a 100mL Solution of 2mM $\text{Co}(\text{C}_5\text{H}_7\text{O}_2)_3$ and subjected to stirring under carefully controlled conditions. Positive and negative controls were incorporated for comparative purposes to ensure accuracy and reliability. Following the filtration process, the supernatant obtained was carefully examined to confirm the presence of NPs. Moreover, the study examined how varying the precursor concentration affected the overall yield of NPs. To achieve this, the concentration of the precursor was systematically varied while keeping the biomass, rotation per minute, and temperature constant. By analyzing the resulting NPs under different precursor concentrations, the study sought to understand the relationship between the concentration of the precursor and the resulting nanoparticle yield. A comprehensive characterization was undertaken to gain further insights into the synthesized NPs. Several techniques, including XRD, FTIR, and TEM, were employed to analyze the spherical structure with the 20.29 nm average size of the NPs and exhibited desirable properties for supercapacitors and photocatalysis [83].

B.A. Omran and the group proposed another green approach using *Aspergillus brasiliensis*. A small amount of *A. brasiliensis* culture was introduced into 100 mL of sterile Sabouraud dextrose broth medium within a conical flask. The flask was then subjected to static conditions at 25°C for 120 hours to allow the culture to proliferate. Once the mycelia had fully developed, they were collected and washed using sterile double distilled water. The mycelia were then transferred to another flask containing sterile water and further incubated for 72 hours. This incubation was performed in a shaking incubator set at a speed of 150rpm. During this period, the flask was subjected to continuous shaking to facilitate the release of mycelial components into the water. After the designated incubation period, the resultant mixture underwent filtration employing Whatman no. 1 filter paper, thereby obtaining a filtrate devoid of mycelial cells, referred to as the mycelial cell-free filtrate, which contains the soluble components released by the mycelia, was collected for further use in the synthesis of CoNPs. By following this process, CoNPs can be successfully synthesized using *Aspergillus brasiliensis*. In order to optimize the biosynthesis of NPs, several physicochemical parameters were systematically investigated. These parameters included the reaction time, pH, temperature, illumination, shaking speed, concentrations, and *A. brasiliensis* biomass dry weights. Each parameter was varied within specific ranges, and its effect on the synthesis process was evaluated. Cobalt Sulfate Heptahydrate ($\text{CoSO}_4 \cdot 7\text{H}_2\text{O}$), which served as the precursor, was mixed with the mycelial cell-free filtrate in a flask to initiate the synthesis. The solution pH was adjusted using 1 mol/L HCl or NaOH to create the desired pH conditions. Subsequently, the flask was subjected to different reaction times ranging from 0 to 96 hours, varying pH levels from 3 to 12, temperatures ranging from 20 to 60°C, illumination conditions, shaking speeds ranging from 0 to 200 rpm, varying concentrations of $\text{CoSO}_4 \cdot 7\text{H}_2\text{O}$ (ranging from 0.5 to 5 mmol/L), and different *A. brasiliensis* biomass dry weights (ranging from 15 to 55 % dry weight/volume). The successful synthesis of NPs was confirmed by observing a noticeable change in color in the mycelial cell-free filtrate solution, indicating the formation of NPs. UV/Vis spectrophotometric analysis was also performed to provide further evidence of nanoparticle formation. By systematically varying these physicochemical parameters and evaluating their impact on the mycosynthesis process, the optimal conditions for synthesizing NPs using *A. brasiliensis* could be determined. The synthesized NPs were subjected to further characterization techniques like FT-IR, XRD, EDX, and UV/Vis to understand their properties better and provide valuable insights into the size distribution found (20–27) nm. Furthermore, synthesized NPs were tested for antimicrobial activity against Gram-positive (*B. subtilis* (ZOI=15.6±0.577) and *S. Aureus* (ZOI=20±0.288)) and Gram-negative (*P. aeruginosa* (ZOI=11.3±0.577) and *E. coli* (ZOI=12±0.288)) bacteria. Dynamic light scattering analysis was carried out to evaluate

the average size distribution and assess the stability of the NPs. This analysis also provided insights into the ionic charge of the NPs by measuring the ZETA potential [84]. Using fungi as promising bio-nano factories for the mycosynthesis of NPs is a relatively new and rapidly growing research area with significant promise.

Li Yang and co-workers used yeast as bio-templates for the CoNPs. In a standard procedure, 0.5 g of yeast powder was washed thrice with physiological saline and ethanol. And then dissolution in 30 ml of double-distilled water. Then, 1.2 g of $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ was introduced into the solution. The system was subjected to continuous magnetic stirring at 60 °C for 3 hours. Following this step, the pH of the system was adjusted from 5.5 to 9 using ammonia. Then, it underwent centrifugation with subsequent washing with double-distilled water and ethanol multiple times. After drying the products at 60 °C, they underwent calcination at 400 °C for 3 hours, followed by natural cooling at room temperature in an air environment, which resulted in the formation of CoNPs. After the synthesis of NPs, different comprehensive characterization processes were undertaken using XRD, SEM, and FT-IR; from them, the average size of NPs was 24nm with anti-reflective properties [85]. The use of fungi as bio-nano factories for the biosynthesis of NPs is a new and fast-growing area of study with enormous promise for advancements in the future.

3. Conclusions

The present study reveals the benefits of the biosynthesis of Cobalt nanoparticles using plant-based extracts, bacteria, and fungi. Plant extracts offer the advantage of acting as capping and stabilizing agents, eliminating the need for additional synthetic chemicals. In the reported literature, the source of cobalt is Cobalt Acetate ($\text{Co}(\text{CH}_3\text{COO})_2$), Cobalt Nitrate ($\text{Co}(\text{NO}_3)_2$), Cobalt Chloride (CoCl_2), Cobalt acetylacetonate ($\text{Co}(\text{C}_5\text{H}_7\text{O}_2)_3$), Cobalt sulfate (CoSO_4) were used. Still option of Cobalt Ammonium Sulfate ($\text{CoSO}_4(\text{NH}_4)_2\text{SO}_4$), Cobalt Ferrite (CoFe_2O_4), Cobalt Carbonate (CoCO_3), Cobalt Formate ($\text{Co}(\text{CHO}_2)_2$), Cobalt Oxalate (CoC_2O_4) and Dicobalt Octacarbonyl ($\text{Co}_2(\text{CO})_8$) exists which can be explored in future. The reported methodologies mainly involve plant/plant part/ microorganism extract, which are easy to obtain and are economically viable also. The cobalt salts taken can be carefully chosen as per availability / cost. The main focus of this comprehensive review paper is to summarize the outcomes from a range of studies that have explored the synthesis of CoNPs utilizing environmentally friendly sources. Additionally, it highlights the potential applications of these NPs and emphasizes the need for green chemistry practices. By encouraging the utilization of green sources for synthesizing metal-based NPs, this review paper aims to inspire readers and contribute to advancing sustainable and environmentally friendly nanotechnology.

Author Contributions

Vaibhav Saini – Literature Survey and Paper writing. Ajay Thakur - Data Analysis. Monika Verma – Critical Analysis and Theoretical Contribution. Ruchi Bharti – Conceptualization. Renu Sharma - Project Supervision.

References and Notes

[1] Santos, C. S. C.; Gabriel, B. F. C. C.; Blanchy, M.; Menes,

- O.; Garcia, D. S. S.; Blanco, M.; Arconada, N.; Neto, V. *Mater. Today: Proc.* **2015**, 2, 456. [\[Crossref\]](#)
- [2] Thakur, A.; Bharti, R.; Verma, M.; Sharma, R. *Curr. Chin. Sci.* **2023**, 3. [\[Crossref\]](#)
- [3] Shameem, M.; Sasikanth, S. M.; Raja, A.; Raman, R. G. *Mater. Today: Proc.* **2021**, 45, 2536. [\[Crossref\]](#)
- [4] Patil, T.; Gambhir, R. P.; Vibhute, A.; Tiwari, A. J. *Cluster Sci.* **2022**, 34, 705. [\[Crossref\]](#)
- [5] Cicha, I.; Priefer, R.; Severino, P.; Souto, E. B.; Jain, S. *Biomolecules* **2022**, 12, 1198. [\[Crossref\]](#)
- [6] Wei, R.; Tang, N.; Jiang, L.; Yang, J.; Guo, J.; Yuan, X.; Liang, J.; Zhu, Y.; Wu, Z.; Li, H. *Coord. Chem. Rev.* **2022**, 462, 214500. [\[Crossref\]](#)
- [7] Ameen, F.; Karimi-Maleh, H.; Darabi, R.; Akin, M.; Ayati, A.; Ayyildiz, S.; Bekmezci, M.; Bayat, R.; Sen, F. *Environ. Res.* **2023**, 221, 115287. [\[Crossref\]](#)
- [8] Harish, V.; Ansari, M. M.; Tewari, D.; Yadav, A. B.; Sharma, N.; Bawarig, S.; García-Betancourt, M.-L.; Karatutlu, A.; Bechelany, M.; Barhoum, A. *J. Taiwan Inst. Chem. Eng.* **2023**, 149, 105010. [\[Crossref\]](#)
- [9] Iravani, S. *Green Chem.* **2011**, 13, 2638. [\[Crossref\]](#)
- [10] Salavati-Niasari, M.; Davar, F.; Mir, N. *Polyhedron* **2008**, 27, 3514. [\[Crossref\]](#)
- [11] Satyanarayana, T. *International Journal for Research in Applied Science and Engineering Technology* **2018**, 6, 2885. [\[Crossref\]](#)
- [12] Tavares, L. M. *KONA Powder Part. J* **2017**, 34, 106. [\[Crossref\]](#)
- [13] Yadav, T. P.; Yadav, R. M.; Singh, D. P. *Nanosci. Nanotechnol.* **2012**, 2, 22. [\[Crossref\]](#)
- [14] Krishnia, L.; Thakur, P.; Thakur, A. *Singapore: Springer Nature Singapore*, **2022** 45. [\[Crossref\]](#)
- [15] Simakin, A. V.; Voronov, V. V.; Kirichenko, N. A.; Shafeev, G. A. *Appl. Phys.* **2004**, 79, 1127. [\[Crossref\]](#)
- [16] Kruis, F. E.; Fissan, H.; Peled, A. J. *Aerosol Sci.* **1998**, 29, 511. [\[Crossref\]](#)
- [17] Swihart, M. T. *Curr. Opin. Colloid Interface Sci.* **2003**, 8, 127. [\[Crossref\]](#)
- [18] Vanecht, E. Gold NPs in Ionic Liquids Prepared by Sputter Deposition
- [19] Lugscheider, E.; Bärwulf, S.; Barimani, C.; Riester, M.; Hilgers, H. *Surf. Coat. Technol.* **1998**, 108, 398. [\[Crossref\]](#)
- [20] Tripathy, S. *Mater. Res. Found.* **2023**, 145, 92. [\[Crossref\]](#)
- [21] Pedersen, H.; Elliott, S. D. *Theor. Chem. Acc.* **2014**, 133, 1476. [\[Crossref\]](#)
- [22] George, S. M. *Chemical Reviews* **2009**, 110, 111. [\[Crossref\]](#)
- [23] Miikkulainen, V.; Leskelä, M.; Ritala, M.; Puurunen, R. L. *J. Appl. Phys.* **2013**, 113, 021301. [\[Crossref\]](#)
- [24] Doll, G. L.; Mensah, B. A.; Mohseni, H.; Scharf, T. J. *Therm. Spray Technol.* **2009**, 19, 510. [\[Crossref\]](#)
- [25] Yang, L.; Chen, J.; Guo, Y.; Zhang, Z. *Appl. Surf. Sci.* **2009**, 255, 4446. [\[Crossref\]](#)
- [26] Bedair, T. M.; Yu, S. J.; Im, S.; Park, B. J.; Joung, Y. K. *J. Colloid Interface Sci.* **2015**, 460, 189. [\[Crossref\]](#)
- [27] Reina, A.; Jia, X.; Ho, J. S.; Nezich, D.; Son, H.; Bulović, V.; Dresselhaus, M. S.; Kong, J. *Nano Lett.* **2009**, 9, 30. [\[Crossref\]](#)

- [28] Jones, A.; Hitchman, M. L. *Royal Society of Chemistry eBooks* **2008**, 1. [\[Crossref\]](#)
- [29] Choy, K.L. *Prog. Mater. Sci.* **2003**, 48, 57. [\[Crossref\]](#)
- [30] Dion, C.; Tavares, J. R. *Powder Technol.* **2013**, 239, 484. [\[Crossref\]](#)
- [31] Bérard, A.; Patience, G. S.; Chouinard, G.; Tavares, J. R. *Sci. Rep.* **2016**, 6, 31574. [\[Crossref\]](#)
- [32] Bhuyan, Md. S. A.; Uddin, Md. N.; Islam, Md. M.; Bipasha, F. A.; Hossain, S. S. *Int. Nano Lett.* **2016**, 6, 65. [\[Crossref\]](#)
- [33] Adachi, M.; Tsukui, S.; Okuyama, K. *Jpn. J. Appl. Phys.* **2003**, 42, 77. [\[Crossref\]](#)
- [34] Ramesh, S. J. *Nanosci.* **2013**, 2013, 1. [\[Crossref\]](#)
- [35] Ealia, S. A. M.; Saravanakumar, M. P. *IOP Conf. Ser.* **2017**, 263, 032019. [\[Crossref\]](#)
- [36] Kammler, H. K.; Mädler, L.; & Pratsinis, S. E. *Chemical Engineering & Technology: Industrial Chemistry-Plant Equipment-Process Engineering-Biotechnology.* **2001**, 24, 583. [\[Crossref\]](#)
- [37] D'Amato, R.; Falconieri, M.; Gagliardi, S.; Popovici, E.; Serra, E.; Terranova, G.; Borsella, E. *J. Anal. Appl. Pyrolysis* **2013**, 104, 461. [\[Crossref\]](#)
- [38] Swihart, M. T. *Curr. Opin. Colloid Interface Sci.* **2003**, 8, 127. [\[Crossref\]](#)
- [39] Tavakoli, A.; Sohrabi, M.; Kargari, A. *Chem. Pap.* **2007**, 61. [\[Crossref\]](#)
- [40] Vodyashkin, A. A.; Kezimana, P.; Prokonov, F. Y.; Vasilenko, I. A.; Stanishevskiy, Ya. M. *Crystals* **2022**, 12, 272. [\[Crossref\]](#)
- [41] Hou, Z.; Jiang, M.; Cao, Y.; Liu, H.; Zhang, Y.; Wang, J.-G. *J. Power Sources* **2022**, 541, 231682. [\[Crossref\]](#)
- [42] Lu, W.; Guo, Y.; Zhang, J.; Yue, Y.; Fan, L.; Li, F.; Dong, C.; Shuang, S. *ACS Appl. Mater. Interfaces* **2022**, 14, 57206. [\[Crossref\]](#)
- [43] Kumar, M.; Jeong, D. I.; Sarwar, N.; Dutta, S.; Chauhan, N.; Han, S. A.; Kim, J. H.; Yoon, D. H. *Appl. Surf. Sci.* **2022**, 572, 151450. [\[Crossref\]](#)
- [44] Pews-Davtyan, A.; Scharnagl, F. K.; Hertrich, M. F.; Kreyenschulte, C.; Bartling, S.; Lund, H.; Jackstell, R.; Beller, M. *Green Chem.* **2019**, 21, 5104. [\[Crossref\]](#)
- [45] Alotaibi, N.; Hammud, H. H.; Otaibi, N. A.; Prakasam, T. *ACS Omega* **2020**, 5, 26038. [\[Crossref\]](#)
- [46] Yang, L.; Zhu, Q.; Yang, K.; Xu, X.; Huang, J.; Chen, H.; Wang, H. *Nanomater.* **2022**, 12, 4065. [\[Crossref\]](#)
- [47] Dobson, J. *Drug Dev. Res.* **2006**, 67, 55. [\[Crossref\]](#)
- [48] Ghanbari, M.; Davar, F.; Shalan, A. *Ceram. Int.* **2021**, 47, 9409. [\[Crossref\]](#)
- [49] Gupta, S.; Fernandes, R.; Patel, R.; Spreitzer, M.; Patel, N. *Appl. Catal., A* **2023**, 661, 119254. [\[Crossref\]](#)
- [50] Jayalakshmi, R.; Jeyanthi, J.; Sidhaarth, K. R. A. *Environ. Nanotechnol., Monit. Manage.* **2022**, 17, 100659. [\[Crossref\]](#)
- [51] Vinosha, P. A.; Manikandan, A.; Preetha, A.; Dinesh, A.; Slimani, Y.; Baykal, A.; Xavier, B.; Nirmala, G. *J. Supercond. Novel Magn.* **2021**, 34, 995. [\[Crossref\]](#)
- [52] Ahmed, K. M.; Iqbal, T.; Siddiqui, S. U. *Pure Appl. Biol.* **2016**, 5, 453. [\[Crossref\]](#)
- [53] Shahzadi, T.; Zaib, M.; Riaz, T.; Shehzadi, S.; Abbasi, M. A.; Shahid, M. *Arabian J. Sci. Eng.* **2019**, 44, 6435. [\[Crossref\]](#)
- [54] Hsu, C.-M.; Huang, Y.-H.; Chen, H.-J.; Lee, W.-C.; Chiu, H.-W.; Maity, J. P.; Chen, C.-C.; Kuo, Y.-H.; Chen, C.-Y. *Mater. Today Commun.* **2018**, 14, 302. [\[Crossref\]](#)
- [55] Vaya, D.; Meena; Das, B. K. *Nanosci. Nanotechnol. Asia* **2019**, 9, 362. [\[Crossref\]](#)
- [56] Tamboli, Q. Y.; Patange, S. M.; Mohanta, Y. K.; Sharma, R.; Zakde, K. R. *J. Nanomater.* **2023**, 2023, 1. [\[Crossref\]](#)
- [57] Bibi, I.; Nazar, N.; Iqbal, M.; Kamal, S.; Nawaz, H.; Nouren, S.; Safa, Y.; Jilani, K.; Sultan, M.; Ata, S.; Rehman, F.; Abbas, M. *Adv. Powder Technol.* **2017**, 28, 2035. [\[Crossref\]](#)
- [58] Hou, H.; Mahdavi, B.; Paydarfard, S.; Zangeneh, M. M.; Zangeneh, A.; Sadeghian, N.; Taslimi, P.; Erduran, V.; Sen, F. *Sci. Rep.* **2020**, 10, 12195. [\[Crossref\]](#)
- [59] Dwivedi, A. D.; Gopal, K. *Colloids Surf., A* **2010**, 369, 27. [\[Crossref\]](#)
- [60] Sharma, J. K.; Srivastava, P.; Singh, G.; Akhtar, M. S. *Materials Science and Engineering: B* **2015**, 193, 181. [\[Crossref\]](#)
- [61] Saeed, M.; Akram, N.; Haq, A. U.; Naqvi, S. A. R.; Usman, M.; Abbas, M.; Adeel, M.; Nisar, A. *Green Process. Synth.* **2019**, 8, 382. [\[Crossref\]](#)
- [62] Rasheed, T.; Nabeel, F.; Bilal, M.; Iqbal, H. M. N. *Biocatal. Agric. Biotechnol.* **2019**, 19, 101154. [\[Crossref\]](#)
- [63] Khalil, A. T.; Ovais, M.; Ullah, I.; Ali, M.; Shinwari, Z. K.; Maaza, M. *Arabian J. Chem.* **2020**, 13, 606. [\[Crossref\]](#)
- [64] Matinise, N.; Mayedwa, N.; Fuku, X.; Mongwaketsi, N.; Maaza, M. *Nucl. Atmos. Aerosols* **2018**. [\[Crossref\]](#)
- [65] Dewi, N. O. M.; Yulizar, Y.; Apriandanu, D. O. B. *IOP Conf. Ser.* **2019**, 509, 012105. [\[Crossref\]](#)
- [66] Anuradha, C. T.; Raji, P. *Appl. Phys. A* **2020**, 126. [\[Crossref\]](#)
- [67] Hafeez, M.; Shaheen, R.; Akram, B.; Abidin, Z. U.; Haq, S.; Mahsud, S.; Ali, S.; Khan, R. T. *Mater. Res. Express* **2020**, 7, 025019. [\[Crossref\]](#)
- [68] Fallahi, M.; Norouzi, B. *Ionics* **2020**, 26, 1951. [\[Crossref\]](#)
- [69] Onwudiwe, D. C.; Ravele, M. P.; Elemike, E. E. *Nano-Struct. Nano-Objects* **2020**, 23, 100470. [\[Crossref\]](#)
- [70] Das, R. K.; Golder, A. K. *Electrochim. Acta* **2017**, 251, 415. [\[Crossref\]](#)
- [71] Edison, T. N. J. I.; Atchudan, R.; Sethuraman, M. G.; Lee, Y. R. *J. Taiwan Inst. Chem. Eng.* **2016**, 68, 489. [\[Crossref\]](#)
- [72] Srivastava, R.; Bhardwaj, S.; Kumar, A.; Singhal, R.; Scanley, J.; Broadbridge, C.; Gupta, R. K. *Nanomater.* **2022**, 12, 4119. [\[Crossref\]](#)
- [73] Rajeswari, V. D.; Khalifa, A. S.; Elfakhany, A.; Badruddin, I. A.; Kamangar, S.; Brindhadevi, K. *Appl. Nanosci.* **2021**, 13, 1367. [\[Crossref\]](#)
- [74] Kombaiiah, K.; Vijaya, J. J.; Kennedy, L. J.; Kaviyarasu, K.; Ramalingam, R. J.; Al-Lohedan, H. A. *J. Nanosci. Nanotechnol.* **2019**, 19, 2590. [\[Crossref\]](#)
- [75] Shahzadi, T.; Zaib, M.; Riaz, T.; Shehzadi, S.; Abbasi, M. A.; Shahid, M. *Arabian J. Sci. Eng.* **2019**, 44, 6435. [\[Crossref\]](#)
- [76] Bibi, I.; Nazar, N.; Iqbal, M.; Kamal, S.; Nawaz, H.; Nouren, S.; Safa, Y.; Jilani, K.; Sultan, M.; Ata, S.; Rehman, F.; Abbas, M. *Adv. Powder Technol.* **2017**, 28, 2035. [\[Crossref\]](#)

- [77] Saravanakumar, P.; Muthukumar, M.; Muthuchudarkodi, R. R.; Ramkumar, P. *International Journal of Recent Research Aspects* **2018**, 918.
- [78] Ikhuoria, E. U.; Omorogbe, S. O.; Sone, B. T.; Maaza, M. *Sci. Technol. Mater.* **2018**, 30, 92. [\[Crossref\]](#)
- [79] Hsu, C.-M.; Huang, Y.-H.; Chen, H.-J.; Lee, W.-C.; Chiu, H.-W.; Maity, J. P.; Chen, C.-C.; Kuo, Y.-H.; Chen, C.-Y. *Mater. Today Commun.* **2018**, 14, 302. [\[Crossref\]](#)
- [80] Shim, H. W.; Jin, Y.; Seo, S. D.; Lee, S. H.; Kim, D. W. *ACS Nano* **2010**, 5, 443. [\[Crossref\]](#)
- [81] Marimuthu, S.; Rahuman, A. A.; Kirthi, A. V.; Santhoshkumar, T.; Jayaseelan, C.; Rajakumar, G. *Parasitol. Res.* **2013**, 112, 4105. [\[Crossref\]](#)
- [82] Iravani, S.; Varma, R. S. *Green Chem.* **2020**, 22, 2643. [\[Crossref\]](#)
- [83] Vijayanandan, A. S.; Balakrishnan, R. M. *J. Environ. Manage.* **2018**, 218, 442. [\[Crossref\]](#)
- [84] Omran, B. A.; Nassar, H. N.; Younis, S. A.; El-Salamony, R. A.; Fatthallah, N. A.; Hamdy, A.; El-Shatoury, E. H.; El-Gendy, N. Sh. *J. Appl. Microbiol.* **2019**, 128, 438. [\[Crossref\]](#)
- [85] Yang, L.; Guan, W.; Bai, B.; Xu, Q.; Yun, X. *J. Alloys Compd.* **2010**, 504, 10. [\[Crossref\]](#)

How to cite this article

Saini, V.; Thakur, A.; Verma, M.; Bharti, R.; Sharma, R. *Orbital: Electron. J. Chem.* **2024**, 16, 293. DOI: <http://dx.doi.org/10.17807/orbital.v16i4.19437>