Mini-Review:

Synthesis and Characterization of Nickel Nanoparticles: Biological and Photocatalytic Properties

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Abstract: *The potential uses of ecologically benign nickel nanoparticle manufacturing in various sectors, such as biomedicine, energy storage, and catalysis, have garnered much interest. This paper covers green approaches to nickel nanoparticle manufacturing, which integrate natural substances as stabilizing and reducing agents with eco-friendly processes. Phytochemicals derived from bacteria, microorganisms, and plant leaf extracts can convert nickel ions (Ni^{2+}) into nickel nanoparticles. Room temperature is used for the synthesis procedure, and neither dangerous compounds nor unusual reaction conditions are used. Using a variety of analytical methods, the resultant nickel nanoparticles were characterized. We also investigate the possibility of using the generated nickel nanoparticles as a cytotoxic, photocatalytic, antioxidant, and antibacterial agents. The antimicrobial activity of nickel nanoparticles demonstrates their potent antibacterial properties, while their antioxidant activity demonstrates their capacity to combat free radicals effectively. Furthermore, nickel nanoparticles' cytotoxic activity demonstrates their capacity to kill cancer cells, and their photocatalytic activity demonstrates their efficiency in breaking down organic contaminants. This review highlights the value of ecologically benign synthetic methods and creates new avenues for developing nickel nanoparticle applications in health and the environment.*

Keywords: *nickel nanoparticles; biosynthesis; biological activity; photocatalytic properties*

INTRODUCTION

One of the most interesting research objects that has become the focus of research in recent years is the synthesis and characterization of materials at nanoparticle sizes. Nanotechnology has made the development of materials with unique qualities and purposes possible, creating a wealth of new scientific and technological potential. One of the most interesting nanomaterials to be developed because of their unique characteristics is metal nanoparticles, one of which is nickel nanoparticles (Ni NPs) [1]. Research on Ni NPs has emphasized this particular substance. Strong magnetic capabilities, superior chemical stability, high electrical and thermal conductivity, and other desirable physicochemical features are all offered by Ni NPs. Ni NPs have numerous industrial and technological uses due to these features. Ni NPs have potential applications in various fields because of their submicroscopic size [2]. Applications of Ni NPs include sensors [3], electronics [1], catalysts [4], and medical treatment [5]. As has been the case recently, the wide application of Ni NPs in various aspects of life encourages the continued development of various methods for synthesizing Ni NPs. The purpose of this development is to obtain nanoparticles with the desired properties [6-7].

Nanoparticles are materials with a primary particle length (single particle) of less than 100 nm [8]. The unique properties of magnetic nanoparticles depend on their chemical composition and microstructural characteristics, such as particle shape and size can be controlled through the fabrication process [9-10]. In general, nanoparticles are grouped into two categories: organic and inorganic nanoparticles. Organic nanoparticles are carbon nanoparticles, while inorganic nanoparticles consist of noble metals (gold and silver), magnetic nanoparticles (nickel, etc.), and semiconductors (titanium oxide and iron oxide) [11-12]. Magnetic nanoparticles (MNPs) are nanoparticles that easily interact with magnetic fields [13]. Elements that can be used consist of iron, cobalt, nickel, and so on, which have magnetic properties and functional groups that cause unique physical properties [14-15]. Its uniqueness can be seen from its function, which can interact at the cellular level [13-16].

METHODS USED FOR LITERATURE COLLECTION

The most recent works published throughout the last five years are included in this review. The journals from which the articles were sourced included Springer Link, Google Scholar, MDPI, ScienceDirect, and Membranes Journal. The order of themes and the order in which references are taken determines the arrangement of reviews. This report provides an in-depth analysis of the most recent advancements in synthesizing Ni NPs. The primary keywords used in various combinations, such as nanoparticle nickel, biosynthesis, green chemistry, and biological materials, are the focus of the search strategy.

■ SYNTHESIS OF Ni NPs

There are two approaches to creating nanomaterials: top-down and bottom-up, as shown in Fig. 1. The idea behind the top-down approach is to break down big chemicals into smaller, even nanoscale components. The bottom-up approach, in contrast, employs the idea of joining smaller ions to react and generate nanosized particles [17-18]. Nanoparticles can be produced using natural products via photochemical, electrochemical, radiolytic, oncolytic, and bioreduction processes. The bioreduction technique falls under the umbrella of nanobiotechnology, a relatively new area of nanotechnology. Nanobiotechnology blends biological concepts with physical and chemical processes to create nanometer-sized particles with particular purposes [19].

The procedures utilized to create nanoparticles span a wide range of recently developed chemical, physical, and biological techniques. The latter approach, nanoparticle synthesis, is not only more sophisticated than chemical and physical approaches [5], but also offers an unmatched versatility. Nanoparticle synthesis can be achieved through chemical or physical means, each with unique applications. The chemical process allows for the creation of nanoparticles from molecular or ionic precursors, while the physical method is adept at breaking down metal solids into tiny nano-sized particles [20].

Both chemical and physical techniques have been employed in several investigations to create nanoparticles. Ghorui et al. [7] produced nickel oxide nanoparticles of different sizes in 2023 by synthesizing Ni NPs via the sol-gel method. Three distinct precursor concentrations (0.1, 0.3, and 0.5 M) were employed in this study. Each sample was kept at pH 8 and burned for 4 h at 500 °C. The study's findings demonstrate the production of spherical, pure, single-phase NiO NPs. As the concentration of the precursor solution rises, so does

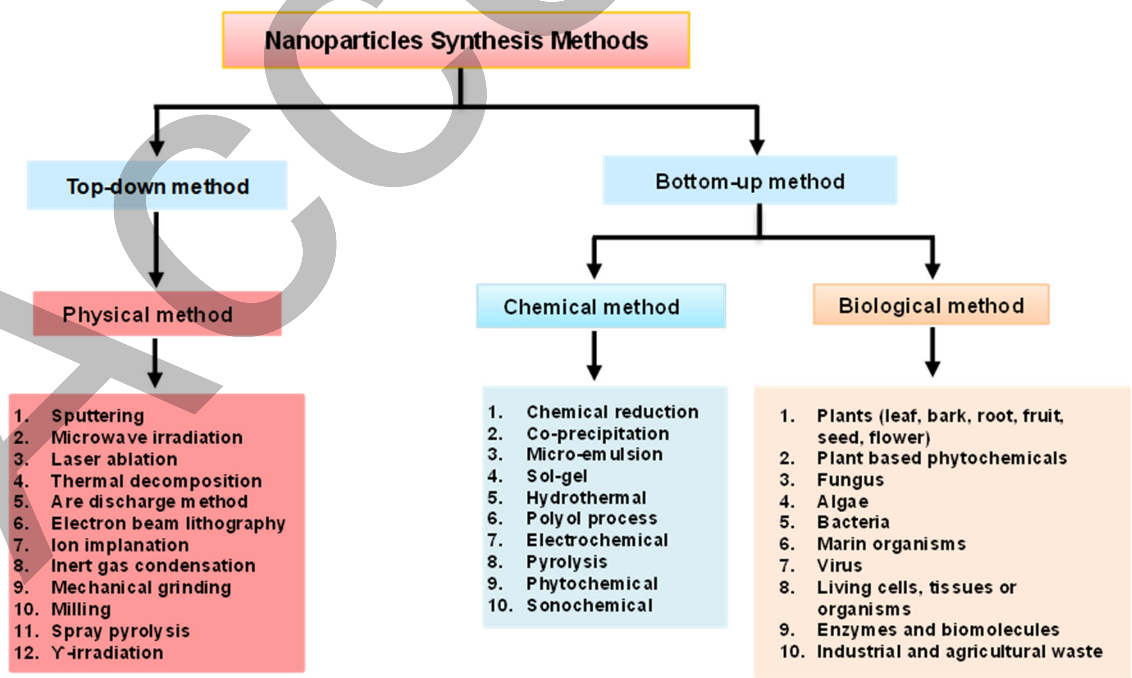

Fig 1. Methods of synthesis of nickel nanoparticles by physical, chemical, and biological methods

the size of the nanoparticles. Every nanoparticle exhibits a near-band edge emission peak at about 390 nm and an absorption peak at around 358 nm, which is in the ultraviolet range. In a subsequent investigation, Shi et al. [21] changed the annealing temperature in the Ni NPs manufacturing process from 100 to 500 °C in 2021. According to FTIR test data, the creation of NiO NPs occurs at a temperature of 300 °C.

The chemical reduction method has advantages over other methods, namely that it is cheap and fast. However, this method is difficult to obtain pure nickel because nickel is easily oxidized with water, so the application becomes very small. The chemical reduction method requires modification of the solution by adding organic compounds such as sodium carboxyl methyl cellulose, tetrabutylammonium bromide, polybutene sulfonate, and cetyltrimethylammonium bromide to control the size of Ni NPs [7]. The synthesis product produced by the hydrothermal method has high crystallinity but is difficult to control; the resulting particles could be finer and have a wide distribution. In addition, this production method is expensive and potentially harmful to the environment and living organisms [22].

Nanoparticle biosynthesis is the technique of synthesizing nanoparticles using living organisms as biological agents, as seen in Fig. 2. This technique utilizes organic molecules found in living organisms. When creating nanoparticles, biological agents can function as stabilizing agents, reducing agents, or both. Organic substances like proteins, carbohydrates, enzymes, and groups of secondary metabolites from plants are used to produce nanoparticles. Utilizing plants and microbes in the reduction technique of biosynthesis is the basis for creating nanoparticles [23-24].

The formulation of biological nanomaterials has been carried out in various ways using materials from different metal ions. Using environmentally friendly principles can be achieved using environmentally friendly solvents and reducing agents [25-26]. There are several drawbacks to creating nanoparticles using chemical and physical means. When specific solvents are used in specific reactions during chemical processes, hazardous

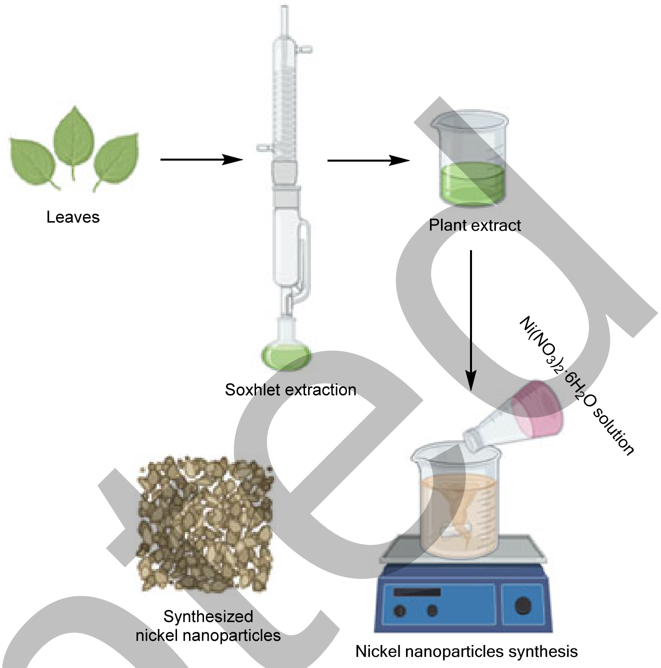

Fig 2. Mechanism of the plant-mediated synthesis of nickel nanoparticles [3]

waste that could harm human health can result. Physical techniques, such as laser ablation, might also provide issues because of their high energy requirements. Therefore, it is of utmost importance to develop an eco-friendly technique that can utilize biosynthetic processes, such as those using plant extracts or animal wastes, to produce nanoparticles in an economical, efficient, and ecologically friendly manner [27-30].

Plant extracts are rich in phytochemicals (phenolics, alkaloids, and flavonoids) and good stabilizing and chelating agents. In addition, plant extracts used as reducing agents can also control the size and shape of the resulting nanoparticles [31]. In 2023, Velsankar et al. [32] researched using *Oryza longistaminta* (brown rice) grain extract in the NiO NPs biosynthesis process. The research results show the formation of Ni NPs in the presence of a plasmon resonance band at a wavelength of 326 nm. The X-ray diffraction pattern (XRD) explains the high crystallinity of NiO NPs with an average crystallite size of 36 nm. The mechanism for reducing Ni^{2+} ions using active phytochemical compounds in brown rice grain extract, namely catechin, is explained in Fig. 3.

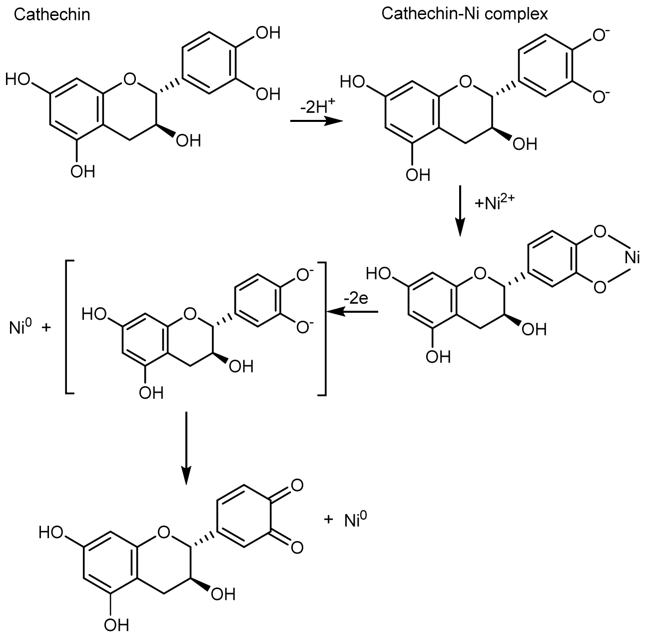

Fig 3. Reduction mechanism of Ni^{2+} ion by catechin [32]

■ CHARACTERIZATION OF Ni NPs

Characterizing Ni NPs is important for understanding the physical and chemical properties that influence their performance in various applications, including biomedicine, electronics, and catalysis. The characterization methods used include various analytical techniques to identify the structure, size, morphology, and optical properties of the nanoparticles. Table 1 presents several characterization techniques to determine the properties of nanoparticles are Fourier transform infrared spectroscopy (FTIR), atomic force microscope (AFM), XRD, UV-vis spectroscopy, and high-resolution transmission electron microscopy.

■ FABRICATION OF Ni NPs

Fabrication of $NiFe_2O_4$ NPs

Nickel ferrite ($NiFe_2O_4$) is a magnetic ferrite material with an inverted spinel structure [46-47]. The specific properties of $NiFe_2O_4$ are mainly influenced by its chemical stability, good saturation magnetization, and unique magnetic structure [48-49]. Table 2 lists several techniques for creating $NiFe_2O_4$ nanocomposites and their uses several fields.

The characteristic properties of $NiFe_2O_4$ nanocomposites cause their photocatalytic properties to be strong against organic pollutants [65-69]. The results

Table 1. Characterization methods of nickel nanoparticles

Types of nanoparticles	Synthesis methods	Precursors	Characterization methods	Ref
NiO	Green synthesis with red rice (*O. longistaminata*) extract	$Ni(NO_3)_2{\cdot}6H_2O$	UV-vis, XRD, FTIR, DLS, HRTEM, EDX	[32]
NiO	Green synthesis with aqueous extract of *Salvadora persica*	$Ni(NO_3)_2{\cdot}6H_2O$	PXRD, FESEM, UV-vis	[33]
NiO	Green synthesis with *Cullen tomentosum* plant extract	$Ni(NO_3)_2{\cdot}6H_2O$	XRD, FESEM, EDAX, FTIR, UV-vis	[34]
NiO	Green synthesis with extracted tea *Camellia sinensis*	$Ni(NO_3)_2{\cdot}6H_2O$	XRD, FTIR, SEM, TEM	[35]
NiO	Sol-gel	$C_4H_6NiO_4{\cdot}4H_2O$	XRD, SEM, EDS, UV-vis, photoluminescence	[36]
$NiFe_2O_4$	Green synthesis with *Eichhornia crassipes* extract	$NiCl_2{\cdot}6H_2O$	UV-vis, XRD, FTIR, SEM, TEM, XPS vibrating sample magnetometer	[4]
$NiFe_2O_4$	Green synthesis with *Tamarindus indica seeds* extract	$Ni_xMg_{1-x}Fe_2O_4$ (x=0; 0.2; 0.4; 0.6)	XRD, FTIR, SEM, EDX, HTEM, XPS, UV-vis	[37]
$NiFe_2O_4$	Green synthesis with *Ixora coccinea* plant	$NiCl_2{\cdot}6H_2O$	XRD, CV, EIS	[38]
$Ni_xMg_{1-x}Fe_2O_4$	Hydrothermal technique	$Ni(NO_3)_2{\cdot}6H_2O$	XRD, Raman, FTIR, SEM, CV	[39]
$NiFe_2O_4$	Green synthesis with *Brassica oleracea* var. capitate (green cabbage)	$Ni(NO_3)_2{\cdot}6H_2O$	XRD, SEM, EDX, FTIR, UV-vis, VSM	[40]
$NiFe_2O_4$	Solvothermal reflux method	$NiC_5H_{14}C_5O_4$	XRD, XPS, FTIR	[41]

Types of nanoparticles	Synthesis methods	Precursors	Characterization methods	Ref
$NiFe_2O_4$	Coprecipitation method	$NiCl_2·6H_2O$	XRD, TEM, SEM, FTIR, UV-vis	[42]
$NiFe_2O_4$/rGO	Green synthesis with peppermint leaf extract	$Ni(NO_3)_2·6H_2O$	XRD, FTIR, UV-vis, FESEM, HRTEM, VSM, XPS	[43]
$NiFe_2O_4$	Green synthesis with *Cocos nucifera* milk extract	$Ni(NO_3)_2·6H_2O$	XRD, FTIR, SEM-EDS, TEM, PL, UV-vis	[44]
$NiFe_2O_4$	Green synthesis with leaf extract of *Terminalia catappa*	$Ni(NO_3)_2·6H_2O$	XRD, FTIR, FESEM, EDAX, HRTEM, UV-vis, VSM	[45]

Table 2. $NiFe_2O_4$ nanocomposite synthesis method and its application

$NiFe_2O_4$ nanocomposites	Synthesis method	Application	Ref
$NiFe_2O_4$/polythiophene	Co-precipitation and chemical oxidative	Adsorption of janus green B and fuchsin	[50]
$NiFe_2O_4$/rGO	Co-precipitation and sonochemical	Adsorption of direct red 81 and basic blue 41	[51]
$NiFe_2O_4$/carbon	Polymerization	Cancer therapy	[52]
$NiFe_2O_4$/MWCNTs	Sol-gel	Removes Cr^{6+} ions	[53]
PPCOT/$NiFe_2O_4$/C-SWCNT	Polymerization	Electrochemical sensor	[54]
Alginate grafted PAMPS/$NiFe_2O_4$	Polymerization	Adsorption of Cu^{2+} and methylene blue	[55]
$NiFe_2O_4$/rGO	Co-precipitation and solvothermal	Adsorption technology	[56]
$NiFe_2O_4$/rGO	Hydrothermal	Supercapacitor	[57]
$NiFe_2O_4$/graphene	Solvothermal	Hydrogen evolution	[58]
rGO/MWCNTs/$NiFe_2O_4$	Hydrothermal and ultra-sonication	Electromagnetic absorption	[59]
$NiFe_2O_4$/carbon	Calcination	Cancer therapy	[52]
$NiFe_2O_4$/CNTs	Hydrothermal	Energy-saving applications	[60]
$NiFe_2O_4$/activated carbon	Hydrothermal and co-precipitation	-	[61]
Polyrhodanine/$NiFe_2O_4$	Polymerization and co-precipitation	Antibacterial	[62]
$NiFe_2O_4$/activated carbon	Hydrothermal	The disappearance of ibuprofen and ketoprofen	[63]
$BaFe_{12}O_{19}$/$NiFe_2O_4$	Co-precipitation	-	[64]

showed that the main peaks shown from the XRD measurements showed the main peaks at 30.27, 35.70, 38.86, 43.40, 54.94, 57.75, 63.02, and 74.48°, which indicated the indices (2 2 0), (3 1 10), (2 2 2), (4 0 0), (4 2 2), (5 1 1), (4 4 0), and (5 3 3) and are indices of face-centered cubic crystal $NiFe_2O_4$. Based on the calculation results, the resulting nanoparticles have an average size of 3 nm. Biosynthesis of $NiFe_2O_4$ nanoparticles has also been carried out by several researchers, including using *Terminalia catappa* extract [70], rosemary extract [71], *Tamarindus indica* seeds [72], *Hydrangea paniculate* flower extract [45], and orange extract [73].

Fabrication of NiO NPs

NiO NPs have high reactivity, a spherical shape on the surface, and environmental friendliness, which makes them ideal for use in biomedical applications [74]. In addition, the electro-discharge method with the addition of H_2SO_4 and ethanol and the ultrasonication method with the addition of NaOH has also been reported to synthesize NiO [75].

Biosynthesis is one method that can be used in the NiO NPs production process. Table 3 presents data from several studies that used biosynthesis methods to produce NiO NPs, as well as the size and application of the resulting nanoparticles. One method of biosynthesis that can be quantified uses plant extracts. Several studies have been carried out using plant extracts in the synthesis of NiO NPs show in Table 2. Akpojevwa et al. [82] used *Gongronema latifollium* extract as a reducing agent and NiO NPs stabilizer. Reducing agents function to reduce Ni^{2+} from positive ions to be uncharged and stabilize stabilizers so that the formed nanoparticles do not agglomerate [11]. The results showed that the formation of Ni NPs with SPR was detected in the wavelength range of 360–390 nm and produced spherical nanoparticles.

Table 3. NiO nanoparticles biosynthesis method, properties, and application

Plant extract and microorganisms species	Precursors	Size of NPs (nm)	Applications	Ref
Oryza longistaminata	$Ni(NO_3)_2{\cdot}6H_2O$	25–50	Antioxidant, antidiabetic, and antibacterial	[32]
Cullen tomentosum	$Ni(NO_3)_2{\cdot}6H_2O$	36 and 31	Antibacterial and anticancer	[34]
Eriochrome black T and Tropeolin OOO (extra pure)	$NiO@WO_3$-Chitosan	15–30	Remediation of organic pollutants from water	[76]
Nigella sativa	$Ni(NO_3)_2{\cdot}6H_2O$	-	Magnetic properties and catalytic performance	[77]
Strychos potatorum	$Ni(NO_3)_2{\cdot}6H_2O$	40–80	Photocatalytic degradation and biological activity	[78]
Microbacterium sp. MRS-1 bacteria	$NiSO_4$	100–500	Ni toxic bioremediation	[79]
Red marine algae	$NiCl_2{\cdot}6H_2O$	32.64	Nanocatalyst	[80]
Sargassum wightii	NiCl	15–20	Antibacterial, antifungal, and cytotoxicity	[20]
Rhamnus triquetra	$Ni(NO_3)_2{\cdot}6H_2O$	65	Antibacterial, antileishmanial, antioxidant, anticancer, antifungal, and enzymes inhibition	[81]

Lingaraju et al. [83] used *Euphorbia heterophylla* (L) extract as a reducing agent, and research conducted with the resulting nanoparticles having a size of 15 nm. XRD patterns observed with index fields (1 1 1), (2 0 0), (2 2 0), (3 1 1), and (2 2 2) correspond to the FCC crystal structures of NiO NPs. The same thing was also obtained from research conducted by Hussein and Mohammed [84] which used grape extract as a reducing agent, with the results of the study showing a peak at an angle of 2 from 37.29, 43.45, 63.11, and 75.35°, which correspond to the (1 1 1), (2 0), (2 2 0), and (3 1 1) fields, which correspond to pure crystalline NiO. In another study, Zhang et al. [85] synthesized NiO NPs using *Calendula officinalis* extract as a reducing and stabilizing agent. The results showed that the average nanoparticle size produced was 60.39 nm. Several studies using the biosynthetic method reported the results of the synthesis of nickel nanoparticles in nano size, with the results of NiO NPs synthesized using *Terminalia chebula* with a size of 18–20 nm [86], extracts of okra plants with a size of 16.9–43.9 nm [87], and extracts of *Ocimum sanctum* with a size of 10–56 nm [88]. *Rhamnus virgata* extract with a size of 24 nm [89]; silk extract, *Zea mays* with size 18.26 nm [90]; and grape extract with a size of 30.19 nm [81].

■ APPLICATION OF Ni NPs

Antibacterial Activity

The antibacterial activity of nanoparticles depends on their size; the large surface area of Ni NPs makes intracellular interactions higher. This is also influenced by the ability of Ni NPs to easily release Ni^{2+} ions in bacterial cells, which causes Ni NPs to be good antibacterial agents. The GL extract used in the NiO NP production process shows that the resulting nanoparticles can be used as a good antibacterial agent, as evidenced by the inhibition zones formed on the growth of Gram-positive and Gram-negative bacteria [83]. Research using lime peel extract in the synthesis of $NiFe_2O_4$ NPs shows the ability of nanoparticles to inhibit the growth of *E. coli*, *S. aureus*, *B. subtilis*, and *K. pneumoniae* bacteria by breaking down cell walls and changing membrane permeability [91].

Research conducted by Hussein and Mohammed [84] using grape extract as a reducing agent showed an increased antibacterial effect if the concentration of Ni NPs was increased [83]. The same thing was also observed in studies using *Calotropis gigantea* extract as a reducing agent and observing its antimicrobial activity by comparing the antimicrobial ability of the resulting nanoparticles compared to the drug chloramphenicol and showing the resulting nanoparticles to have the same ability as chloramphenicol in inhibiting microbial growth [21].

Antioxidant Activity

Antioxidants can destroy free radicals, prevent cancer, and regenerate damaged skin cells. Several studies have shown that metal nanoparticles have excellent antioxidant abilities. The antioxidant ability of metal nanoparticles was observed by comparing the ability of the nanoparticles to inhibit the activity of the 2,2-diphenyl-1-picrihydrazyl (DPPH) free radical and showing that with the addition of metal nanoparticles, the activity of DPPH would be inhibited [91]. Research using *Calendula officinalis* extract, which can inhibit the growth rate of DPPH [73]. Research using lime peel extract in the synthesis of $NiFe_2O_4$ NPs shows that the ability of nanoparticles as antioxidants will increase with increasing concentrations of NPs [92].

Cytotoxic Activity

Cancer is a disease that is the main cause of high mortality rates in both developing and developed countries. Silver nanoparticles can inhibit growth and cause cancer cell death [93]. Research using grape extract as a reducing agent and testing its cytotoxicity on human brain and breast cancer cells showed that the addition of Ni NPs at a concentration of 0.02 M could lead to a 75% reduction in cancer cell viability, whereas increasing the concentration of the nanoparticles resulted in decreased cancer cell death. Additionally, the nickel is reduced in the process [90]. Synthesis of NiO NPs using plant extracts of *Euphorbia heterophylla* (L) and observing their cytotoxic activity against cancer cell lines showing cell viability showed decreased activity with the addition of nanoparticles [94].

Several studies reported that Ni NPs synthesized with ethnomedicinal plant extracts could prevent the growth of cancer cells. Size is one of the parameters that have a significant role in the anticancer activity of Ni NPs. The smaller the size of the resulting nanoparticles, the better the anticancer activity, which is influenced by the better penetration properties of smaller particle sizes. The particle size that effectively inhibits cancer cell growth is smaller than 100 nm [95-96]. The same thing was shown by studies using Calendula extract as a reducing agent and observing its anticancer activity, showing that the resulting Ni NPs can be used as a drug in treating cancer in humans [85]. Research that has been carried out using lime peel extract in the synthesis of $NiFe_2O_4$ NPs shows its ability to inhibit the growth of HeLa cancer cells by inhibiting their metabolic activity [91].

Photocatalytic Activity

Calotropis gigantea leaf extract was used in the biosynthesis process of Ni NPs and observed the catalytic potential of the Ni NPs formed on the adsorption activity of methylene blue, which showed an absorption efficiency of 97.8% for the Ni NPs catalyst and 98.6% for the NiO NPs catalyst [22]. Similar studies have also been carried out using *Camellia sinensis* extract as a reducing agent and observing the catalytic potential of nanoparticles on the degradation of CV dyes. The degradation increased with increasing irradiation time and reached 99.5% after irradiation for 42 h under sunlight [97].

Photocatalytic degradation of meropenem using a visible light source using a $NiFe_2O_4$/MOF-808 nanocomposite with the best efficiency using a mass ratio of $NiFe_2O_4$:MOF-808 with a ratio of 1:2 at pH 6 [98]. The hydrothermal method has synthesized $NiFe_2HAI_4$ nanoparticles coated onto cellulose nanofibers (CNF) to produce cellulose-$NiFe_2HAI_4$ nanocomposite (CNF-$NiFe_2HAI_4$). Table 4 illustrates how the $NiFe_2O_4$ nanocomposite uses light to degrade various organic contaminants. The large surface area and increased thermal stability of the photocatalyst, SCNF-$NiFe_2HAI_4$ (2.5:1) composite ratio, showed a removal efficiency of 98.6% using a 50 mg catalyst in dye degradation [98]. When H radicals and dye molecules interact, mineral acids and H_2O products are produced, which is how dye degradation happens. The photocatalytic activity of $NiFe_2O_4$/GO nanocomposites in conjunction with an enzymatic mechanism results in excellent performance decolorization under UV light [11].

■ FUTURE PROSPECTS

Biosynthesis of Ni NPs offers an environmentally friendly approach to nanomaterial production but faces various challenges that need to be overcome in the future. One of the main challenges is optimizing the synthesis conditions to achieve precise control over the nanoparticles' size, morphology, and purity. A deep understanding of the molecular mechanisms underlying nanoparticle formation is necessary to improve the

Table 4. Photocatalytic effects of $NiFe_2O_4$ nanocomposites on organic pollutants

Pollutant type	$NiFe_2O_4$ nanocomposites	Light source	Degradation efficiency (%)	Degradation time (min)	Ref
RB	$NiFe_2O_4/ZnWO_4$	Sunlight	98.00	70	[69]
Azo fuchsine	$NiFe_2O_4$/sepiolite	Microwave radiation	100.00	5	[99]
Methyl parathion	$NiFe_2O_4$/sepiolite	Microwave radiation	100.00	3	[99]
Crystal violet	$NiFe_2O_4$/sepiolite	Microwave radiation	100.00	6	[99]
Azo fuchsine	$NiFe_2O_4$/diatomite	Microwave radiation	90.50	5	[99]
Azo fuchsine	$NiFe_2O_4$/kaolinite	Microwave radiation	68.20	5	[99]
MB	$NiFe_2O_4$@GO	UV light	100.00	120	[99]
MB	$BiVO/NiFe_2O_4$	Sunlight	95.00	240	[100]
MB	$BiVO/NiFe_2O_4$	Sunlight	98.00	30	[101]
MB	$ZnS/NiFe_2O_4$	Sunlight	93.00	120	[102]
TC	Sulphur-doped carbon nitride/$NiFe_2O_4$Pectin/NiFeO	LED light	97.00	60	[103]
MB	Pectin/$NiFe_2O_4$	Visible light	99.57	35	[104]
TC	$NiFe_2O_4$/BiWO	Visible light	96.81	96	[105]
RB	$NiFe_2O_4$@hydroxyapatite-Sn^{2+}	Solar light	99.20	40	[106]
Malachite green	$rGO/NiFe_2O_4$	Visible light	96.50	120	[107]
Doxycycline	$NiFe_2O_4$/MWCNTs/BiOI	UV light	92.18	150	[108]
Acid red 14	$NiFe_2O_4$-mixed metal oxides	Visible light	100.00	165	[109]

efficiency and consistency of the biosynthesis process. The scalability of biosynthetic production is also an obstacle, as environmentally friendly methods are often tricky to implement on an industrial scale without losing efficiency or quality. In addition, variations in the composition of biological extracts can affect the reproducibility of synthetic results, demanding better standards in the selection and processing of biological agents.

Assessment of the toxicity and environmental impact of biologically synthesized Ni NPs is still less comprehensive, so further research is needed to ensure the safety and sustainability of the use of these nanoparticles in various applications. Regulatory compliance and developing clear guidelines are important challenges to ensure safe and effective implementation. Integrating biosynthesis with advanced technologies such as nanotechnology, biotechnology, and materials science requires a complex interdisciplinary approach. Additionally, there needs to be investment in research and development to overcome technical challenges and increase the commercialization potential of biologically synthesized Ni NPs. Overall, although its biosynthesis has great potential to produce sustainable and environmentally friendly nanomaterials, technical, regulatory, and research challenges must be overcome to realize widespread applications of this technology in the future.

■ CONCLUSION

The production of $NiFe_2O_4$ and NiO NPs can be achieved using a variety of techniques, which can be broadly categorized into three categories: chemical, physical, and biological. There are several drawbacks to creating nanoparticles using chemical and physical means. When specific solvents are used in specific reactions during chemical processes, hazardous waste that could harm human health can result. Physical techniques, such as laser ablation, also cause issues because of their high energy requirements. As a result, a cost-effective, efficient, and ecologically friendly alternative method for creating nanoparticles was created: the biosynthetic approach, which uses either plant extracts or animal waste. Every technique used to create nanoparticles results in particles smaller than 100 nm. The outcomes of the numerous investigations that have been examined demonstrate the potential of Ni NPs as photocatalyst, antibacterial, antioxidant, and anticancer agents.

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CONFLICT OF INTEREST

The author has no conflicts of interest that would lead to them purposefully benefiting from this review.

AUTHOR CONTRIBUTIONS

Fadliah, Indah Raya, and Ahyar Ahmad led the study, with the support and collaboration of Paulina Taba, Maming Gaffar, Muhammad Burhannudinnur, and Fadliah in data gathering. Tri Widayati Putri, Arfiani Nur, Andi Nur Fitriani Abubakar, and Rachmin Mudadi, in a collaborative effort, carried out the data analysis and interpretation. Fadliah, Ahyar Ahmad, and Indah Raya, in a joint effort, prepared the manuscript. Ahmad Fudhail Majid, Irham Pratama, M. Yasser, Sulistiani Jarre, and Harningsih Karim, with their collective statistical analysis and figure preparation, contributed to the research. The work was edited by Ahyar Ahmad, Indah Raya, and Fadliah, who ensured the intellectual content was of utmost importance. Through their collaborative contributions, each author shaped the final manuscript and discussed the findings.

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