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REVIEW ARTICLE

Gold, iron and silver nanoparticles: Synthesis, characterization and applications in antibacterial, cytotoxic and wastewater treatment: A comprehensive review

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Abstract

Advances in nanotechnology have positioned metal nanoparticles, especially gold (Au), iron (Fe) and silver (Ag), at the forefront of innovations in biomedical, environmental and catalytic applications. These qualities have enabled wide-ranging applications in wastewater cleanup, bio sensing, cancer treatment and antibacterial treatment. However, the synthesis method, structural characteristics, surface chemistry and colloidal stability of these nanoparticles significantly impact their performance and safety. This paper covers in detail the mechanics, benefits, drawbacks and environmental effects of both conventional and green synthesis techniques for creating Au, Fe and Ag nanoparticles. To illustrate their significance in determining nanoparticle size, shape, composition and surface functionality, key characterization techniques, including UV-Vis spectroscopy, transmission electron microscopy (TEM), scanning electron microscopy (SEM), X-ray diffraction (XRD), forier transform infrared (FTIR) spectroscopy, dynamic light scattering (DLS) and zeta potential, are reviewed. The review also examines these nanoparticles' cytotoxicity to both healthy and malignant cells, as well as their antibacterial mechanisms, including membrane rupture, the production of reactive oxygen species (ROS) and biomolecular interference. Their functions in wastewater treatment are also investigated, with particular attention to catalytic reduction, heavy-metal removal, dye degradation and disinfection procedures. Significant obstacles still exist despite tremendous advancements, such as concerns about the toxicity of nanoparticles, their persistence in the environment, their economic viability and the scalability of green synthesis techniques. This analysis tackles existing gaps and proposes the creation of safer, more sustainable and application-oriented nanomaterials.

Keywords: Ag; antibacterial; Au; cytotoxicity; Fe; green methods; wastewater

Introduction

Noble and transition metal nanoparticles, particularly those of gold (Au), iron (Fe) and silver (Ag), have attracted a lot of scientific and commercial attention because to their distinct physicochemical, optical and catalytic characteristics when compared to bulk materials. These metal nanoparticles have been developed over the past 20 years using a range of synthesis methods, including physical, chemical and green biological approaches, driven by the growing need for efficient wastewater treatment technologies, sophisticated biomedical tools and effective antimicrobial agents (1, 2).

The biological interactions, toxicity profiles and catalytic activity of nanoparticles are determined by their size, shape, stability and surface chemistry, all of which are significantly influenced by the synthesis procedure. Confirming nanoparticle formation, analyzing crystalline structure, determining dispersion stability and comprehending surface functional groups all depend on characterization techniques like ultraviolet-visible (UV–Vis) spectroscopy, transmission electron microscopy (TEM), scanning electron microscopy (SEM), X-ray diffraction (XRD), forier transform infrared (FTIR) spectroscopy, dynamic light scattering (DLS) and zeta potential analysis. Through mechanisms such as membrane disruption, oxidative stress induction and interference with cellular processes, Au, Fe and Ag nanoparticles exhibit promising antibacterial activity, making them excellent options for combating infections resistant to multiple drugs. Additionally, its cytotoxicity serves a dual purpose: it enables targeting specific cancer cells but requires careful evaluation to prevent unintended biological damage (3, 4).

In addition to their catalytic and redox-active properties, these nanoparticles have demonstrated high efficacy in environmental remediation by degrading dyes, reducing harmful pollutants and adsorbing heavy metals from wastewater. To guide future developments and ensure the safe, efficient use of Au, Fe and Ag nanoparticles in biomedical and environmental systems, a thorough evaluation of synthesis strategies, analytical methods and application-specific performance is crucial, given the rapid growth of research in this field (5–7).

Nanoparticle science has advanced rapidly, yet several significant gaps remain. Few studies offer a comprehensive comparison of Au, Fe and Ag nanoparticles across both sectors; instead, most current research focuses on either biological or environmental applications. Furthermore, it is frequently unclear how the production process, surface chemistry of nanoparticles and biological/ecological performance are related. It can be challenging to establish a direct correlation between nanoparticles' characteristics and their antibacterial, cytotoxic, or catalytic activities due to insufficient characterization data. Furthermore, most published research is conducted in laboratory settings that are not representative of natural environments or physiological systems, raising questions about the stability, toxicity and long-term behavior of nanoparticles. To create clear design guidelines and facilitate safer, more efficient nanoparticle use, a thorough review to fill these gaps is required (8–10).

The novelty of this study lies in its integrated and comparative perspective on Au-, Fe- and Ag-based nanoparticles, linking synthesis routes, physicochemical characterization, antibacterial mechanisms and wastewater treatment performance within a single framework. Unlike studies that focus on individual nanoparticles or isolated applications, this work highlights the synergistic advantages of hybrid and composite nanostructures for multifunctional wastewater treatment, while simultaneously addressing practical challenges such as recoverability, durability and sustainability. This holistic approach provides valuable insights into translating nanoparticle technologies from laboratory research into scalable, eco-friendly and real-world applications.

The goal of this review is to methodically assess the synthesis, characterization and functional uses of Au, Fe and Ag nanoparticles, with a focus on their roles in wastewater treatment, cytotoxicity and antibacterial activity. The review aims to highlight key factors that affect nanoparticle performance in biomedical and environmental systems, incorporate recent scientific advancements and identify emerging trends.

Synthesis and surface functionalization of Au, Fe and Ag nanoparticles

Nanomaterials have lately attracted the interest of researchers due to their unique qualities. Researchers have been generating them using various preparation methods. Since production costs and environmental safety are critical factors in practical applications, several synthesis methods have been developed. These techniques are generally categorized into four main types: chemical, physical, biological and green synthesis (11). Many elements have been converted from standard size to nano size using these methods, such as Ag, Au, Fe, TiO_2, Cu and Zn (12-17). The current study reviewed 3 elements: gold (Au), silver (Ag) and iron (Fe) nanoparticles. Fig. 1 shows various synthesis methods for nanoparticles, including chemical, green and physical approaches.

The studies summarized in Table 1 showcase various innovative methods for synthesizing Au, Fe and Ag nanoparticles (NPs) and their composites, demonstrating their effectiveness in wastewater treatment, dye degradation and antimicrobial uses. Gold-based nanocomposites were predominantly synthesized via chemical and green routes, including in situ synthesis, photoinduction and biogenic methods. For instance, cotton-Au and cellulose-Au composites prepared by in situ and photoinduction techniques demonstrated uniform particle distribution, spherical morphology (8–20 nm) and excellent catalytic and antibacterial performance. Green chemistry methods utilizing natural extracts or biopolymers, such as silk, chitosan and bacterial cellulose (BC), enable the sustainable synthesis of AuNPs while preserving the matrix structure. These biogenic and green syntheses enhance antioxidant activity, UV protection and dye degradation efficiency, underscoring their potential for eco-friendly textile and environmental applications (18–20).

Similarly, AgNPs have been extensively synthesized through green and biogenic methods, which employ plant-derived phytochemicals as both reducing and capping agents. These eco-friendly syntheses yielded nanoparticles with potent antibacterial, antioxidant and cytotoxic effects. Studies utilizing extracts from *Acacia raddiana*, *Pinus sylvestris* and *Althaea officinalis* demonstrated not only the simplicity and sustainability of the green synthesis method but also the production of highly stable and bioactive Ag NPs. Furthermore, biogenic synthesis using bacterial or fungal extracts enhanced the uniformity and functional performance of Ag NPs, making them suitable for wastewater purification, biosensing and biomedical uses (21, 22).

Collectively, these findings underscore that green and biogenic synthesis methods are not only sustainable alternatives to conventional chemical synthesis but also improve nanoparticle

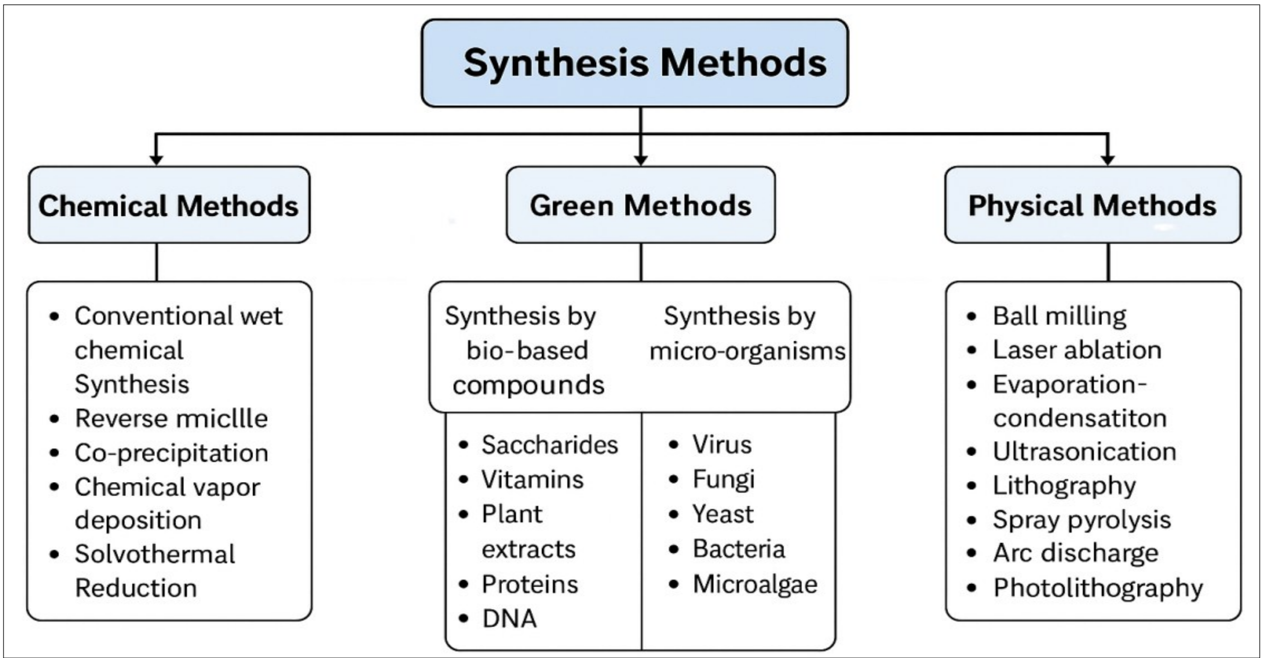

Fig. 1. Schematic representation of various synthesis methods for nanoparticles, including chemical, green and physical approaches.

Table 1. Summary of studies on Au, Fe and Ag nanoparticles and their composites for biomedical applications

No	Metals	Composites	Source	Method	Results	Application	Ref`
1	Au	Cotton-Au	Chemical	In situ synthesis	The study successfully synthesized composites of cotton-Au nanoparticles, which were characterized and found to have a particle size of 8-20 nm, spherical in shape. Using conventional colors did not affect the catalytic qualities of the AuNPs on the fabric. Cotton fabric coated with AuNP and utilized as a flexible active substrate displayed enhanced dye Raman signals	Anti-bacterial activity	(31)
2	Au	Cellulose- Au	Chemical	Photoinduction method	The experimental results demonstrate that AuNPs are uniformly dispersed and well-bound to the BC matrix and the three-dimensional porous structure of BC is sustained. The acidic condition facilitates the synthesis of AuNPs by using BC in aqueous solution	Dyes inspection	(32)
3	Au	Cotton-Au, leather-Au Silk fabric- Au	Chemical-Natural	Green chemistry	This work provides a first step toward the biofunctionalization and coloring of different textiles using green technology, which should lead to new opportunities for innovation in the apparel and textile industries	Anti-bacterial activity	(33)
4	Au	/	Chemical-Natural	Biogenic synthesis	Cotton textiles were dyed using the gold nanoparticle, which was created in a variety of hues. To ascertain the color fastening, the colored cotton fabrics were subjected to a range of stressful conditions	Dyeing cotton fabrics	(34)
5	Au	/	Chemical-Natural	Biogenic synthesis	The pseudo first order kinetic model was used to describe the photodegradation process. These findings demonstrate that Alpinia nigra is a promising bioresource to produce of Au-NPs with a wide range of uses	Anti-bacterial activity, antioxidant and anti-fungal	(35)
6	Au	/	Chemical-Natural	Biogenic synthesis	These findings imply that produced gold nanoparticles mediated by *B. marisflavi* are a promising nano-catalyst in the breakdown of methylene blue and Congo red	Catalytic dye degradation	(36)
7	Au	/	Chemical-Natural	Green method	The authors of this study used various organic pollutants, including methyl orange and methylene blue, to catalyze the action of Au NPs. When compared to normal ascorbic acid using the conventional 1,1-diphenyl-2-picrylhydrazil technique, it likewise demonstrated good antioxidant activity. Therefore, our study concluded that Au NPs mediated by ECBP would be a suitable material for dye degradation and antioxidant activity	Antioxidant activity, Catalytic activity	(37)
8	Au	Au- asparagine	Chemical-Natural	Green method	The degradation reactions followed pseudo first order kinetics and all the dyes broke down with N90 % efficiency in 30 minutes. The rehabilitation of textiles and other industrial waste fluids contaminated with organics such as dangerous dyes, pigments and surfactants can benefit greatly from the catalytic properties of gold nanoparticles	Catalytic activity	(38)
9	Au	Cotton-A	Chemical-Natural	Green method	It showed that the cotton fabric coated with AuNPs extract exhibited more antibacterial activity against Escherichia coli than other test materials. Comparing extract-containing AuNPs-coated cotton fabric to uncoated and neat extract-coated cotton fabric, UV-DRS study revealed better UV-blocking properties	Antibacterial and UV blocking applications	(39)
10	Au	Chitosan-Au	Chemical-Natural	Green method	The study's conclusions demonstrate the potential of applying Au NPs to biomass-derived materials for ecologically friendly dye remediation, offering a long-term solution to wastewater dye contamination	Catalytic degradation of dyes	(40)
11	Fe	Fe_2O_3	Chemical-Natural	Green method	This study validates the effectiveness of green iron particles derived from grape leaves in decolorizing reactive dyes and provides additional recommendations for treating textile wastewater	Textile dye decolorization and wastewater treatment	(41)
12	Fe	Fe_2O_3	Chemical-Natural	Green method	The results showed that P. granatum seed extract is a promising biomolecule for the synthesis of Fe_2O_3 NPs, as it is an environmentally friendly, economical and green process. Fe_2O_3 NPs may be utilized for wastewater dye degradation	Photocatalytic Activity and degradation of textile dye	(42)
13	Fe	Fe_2O_3	Chemical	Chemical synthesis	The morphological data analysis of the plant shows that the catalyst Fe_2O_3 NPs-induced solar-irradiated wastewater exhibits less detrimental impact on plant morphology. We applied the treated wastewater to the plant to examine the reusability of the treated TWW	Wastewater	(43)
14	Fe	Fe_2O_3	Chemical-Natural	Biogenic synthesis	The mycosynthesized Fe_2O_3 Nanoparticles demonstrated antibacterial activity and provided an environmentally benign, sustainable and efficient method for decolorizing navy blue and safranin dyes	Dyes Removal and Antibacterial Activity	(44)
15	Fe	Fe	Chemical-Natural	Green method	In the present study, the most effective antioxidant treatment (FeNP III) exhibited a superior antimicrobial profile; however, this was not observed in relation to the amount of phenolic compounds, indicating that iron plays a significant role in both the antioxidant and antimicrobial activities of FeNPs	Antioxidant and antimicrobial activity	(45)

16	Fe	Fe_2O_3	Chemical-Natural	Green method	The bacterium-produced Fe_2O_3-NPs showed considerable ability to suppress biofilm formation and efflux pump activity, as well as significant antimicrobial action, especially against Gram-positive bacteria, providing a promising approach to AMR	Antibacterial, anti-biofilm and anti-virulence	(46)
17	Fe	Fe_2O_3	Chemical-Natural	Green method	The nanoparticles produced demonstrated a modest level of antibacterial activity against various bacterial species, including *Klebsiella* spp., *E. coli*, *Pseudomonas* spp. and *S. aureus*. Although the maximal concentrations of nanoparticles' cytotoxic effect on HeLa, BHK-21 and Vero cell lines were found to be hazardous, their exceptional activity against these cell lines suggests that they may be helpful for causing tumor cell destruction	Photocatalytic and antibacterial activity	(47)
18	Fe	Fe	Chemical-Natural	Green method	The degradation of crystal violet dye under 80 % sunlight irradiation revealed the photocatalytic capability of the produced FeONPs. Therefore, Ruellia tuberosa-synthesized FeONPs may be crucial for eliminating bacterial infections and degrading dyes in the bioremediation of household and commercial wastewater	Antimicrobial properties and photocatalytic degradation	(48)
19	Fe	Fe_2O_3	Chemical-Natural	Green method	According to the results, 200 ppm of MnFe or TnFe should be applied to produce an intense antibacterial action. To evaluate the use of green nFe oxides in foods that are kept, more research is necessary	Antimicrobial	(49)
20	Fe	Fe_2O_3	Chemical-Natural	Green method	The findings demonstrated a significant dose-dependent suppression of cancer cell proliferation	Catalytic activity and Anticancer Activities	(50)
21	Ag	Ag	Chemical-Natural	Green method	The present research demonstrates the potential benefits of Acacia raddiana for the environmentally benign synthesis of AgNPs and their efficacy as heavy metal sensors for the environment, exhibiting a strong colorimetric identification capability	Environmental sensor	(51)
22	Ag	Ag	Chemical-Natural	Green method	The obtained results indicated that AgNPs based on *C. garcini* might be a viable option for a number of biological uses. The manufacture of AgNPs based on green extracts has the potential to yield multi-potential, inexpensive and environmentally friendly nanoparticles	Antibacterial activity, Anticancer activity, Larvicidal activity and antioxidant	(52)
23	Ag	Ag	Chemical-Natural	Green method	AgNPs have the potential to be employed effectively in cancer therapeutic approaches and to limit the proliferation of cancer cells and the results showed that anzroot plants may be used as an effective reducing agent for AgNPs production	Cytotoxic effects	(53)
24	Ag	Ag	Chemical-Natural	Green method	*E. coli* was used to test the antibacterial activity of the AgNPs and the samples demonstrated inhibitory effects at varying doses of silver. The biogenic AgNPs demonstrated their suitability as a substrate for Surface-Enhanced Raman Scattering (SERS) by promoting an enhanced methylene blue Raman signal	Antibacterial activity	(54)
25	Ag	Ag	Chemical-Natural	Green method	When compared to aqueous extracts, the seed extract was found to be a superior antioxidant and AgNPs demonstrated a highly biocidal effect against both test pathogens. According to the results, *P. sylvestris* seed extract can be used to create stable silver nanoparticles, which are good antibacterial agents and show promise as remedies for cosmetic shame	Cosmetic embarrassment, Antibacterial activity and antioxidant	(55)
26	Ag	Ag	Chemical-Natural	Green method	The results of this work demonstrate that nisin's antibacterial activity can be enhanced by incorporating it into the AgNP interface using a green chemical synthesis technique. To increase nisin's efficacy, the method could be applied to create an antibacterial formulation	Antibacterial activity	(56)
27	Ag	Ag	Chemical-Natural	Biogenic synthesis	AgNPs with strong antibacterial and antioxidant properties, as well as prospective uses in industry and biomedicine, have been produced biogenically in this study. To the best of our knowledge, our work is the first to employ *C. nitida* pod extract for environmentally friendly nanoparticle manufacturing	Antibacterial and antioxidant activities and application as a paint additive Footnote	(57)
28	Ag	Ag	Chemical-Natural	Biogenic synthesis	Against a range of harmful gram-positive and gram-negative bacteria, AgNPs produced using the green technique demonstrated a potent antibacterial action	Antibacterial	(58)
29	Ag	Ag	Chemical-Natural	Biogenic synthesis	This study was unique in that it utilized *A. officinalis* leaf extract as a capping reagent for the environmentally friendly and clean production of silver metallic nanoparticles. The outcomes obtained demonstrated significant cytotoxic and antibacterial activities against cancer cell lines and pathogenic microbes, advancing the field	Antibacterial and cytotoxicity	(59)
30	Ag	Ag	Chemical-Natural	Biogenic synthesis	Future treatments for microbes that are ordinarily resistant to conventional antibiotics or antifungal medications may greatly benefit from these findings	Biocidal property (Antibacterial Activity)	(60)

stability, surface reactivity and multifunctionality. The variety of synthetic routes ranging from in situ and photoinduced synthesis to green and microbial-mediated methods enables precise control over particle morphology and functionality. Therefore, Au, Fe and Ag nanocomposites synthesized through these approaches offer significant potential for integrated environmental remediation systems, combining pollutant degradation, antimicrobial action and material reusability under environmentally benign conditions.

Characterization techniques of Au, Fe and Ag nanoparticles

Characterization of nanomaterials is a critical step for determining their chemical, physical and biological properties. As mentioned in Table 1, several techniques have been employed to characterize silver, gold and iron nanoparticles, including SEM, EDX, FTIR, XRD and TEM. These techniques are used to determine the surface condition, shape and size of nanomaterials, as well as their surrounding chemical composition. Fig. 2 shows the SEM and TEM images of Au nanoparticles obtained in the previous study that display the surface morphology, shapes and sizes of the particles (23). They detected homogeneous distribution, spherical shapes and 27–50 nm in their sizes. This can explain the advantages of these techniques in the characterization process.

The chemical composition of the nanoparticles and the surrounding materials around them was detected using XRD and FTIR. The study reported the synthesis of nanoparticles and their chemical composition characterization, with the FTIR results presented accordingly (24). The results obtained for FTIR are shown. The stretching vibration of the O-H bond is linked to a strong bond at 3740 cm^{-1} and 3584 cm^{-1}. The stretching vibration mode of NH is attributed to the peak at 2175 cm^{-1}. The peak indicates the isothiocyanate band at 2175 cm^{-1}, which is primarily due to NCS stretching. The amino acid contains the CN stretching vibration at 1653 cm^{-1}. Furthermore, alkenes may be represented by the band at 1560 cm^{-1}, whereas conventional antibiotics or antifungal medications may be represented by the CO stretching at 1027 cm^{-1}. Moreover, the XRD results show that seven distinct peaks were observed at 2θ, including at 17° [012], 23° [104], 28° [110], 37.5° [113], 46.5° [202], 57.2° [116] and 78.5° [214]. The XRD spectra were collected in the 2θ range of 10° to 80°. These two techniques clearly explain the composition of the Fe nanoparticles, as shown in Fig. 3.

Ultraviolet-visible (UV-Vis) spectroscopy is considered the most common technique used as a first step to confirm the conversion of metals to metal nanoparticles. Fig. 4a shows the results obtained from previous studies, which explain the UV-vis spectroscopy of Ag nanoparticles and indicate an absorbance peak at 436 nm, suggesting the conversion of silver ions to AgNPs. Moreover, the EDX is one of the significant techniques to evaluate the presence of material clearly at the nanoscale (25). Fig. 4b shows the EDX analysis of AgNPs, with a peak at 3 keV confirming the presence of silver (25). This provides a quick overview of the

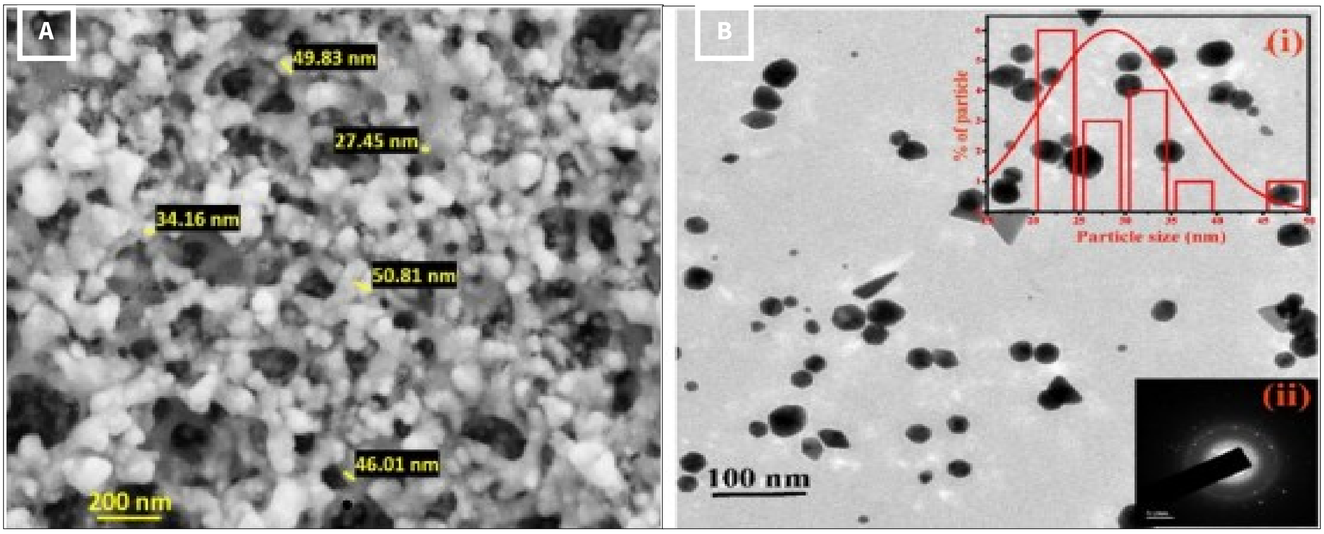

Fig. 2. The morphology of Au nanoparticles (a) in SEM and (b) the size and shape in TEM (38).

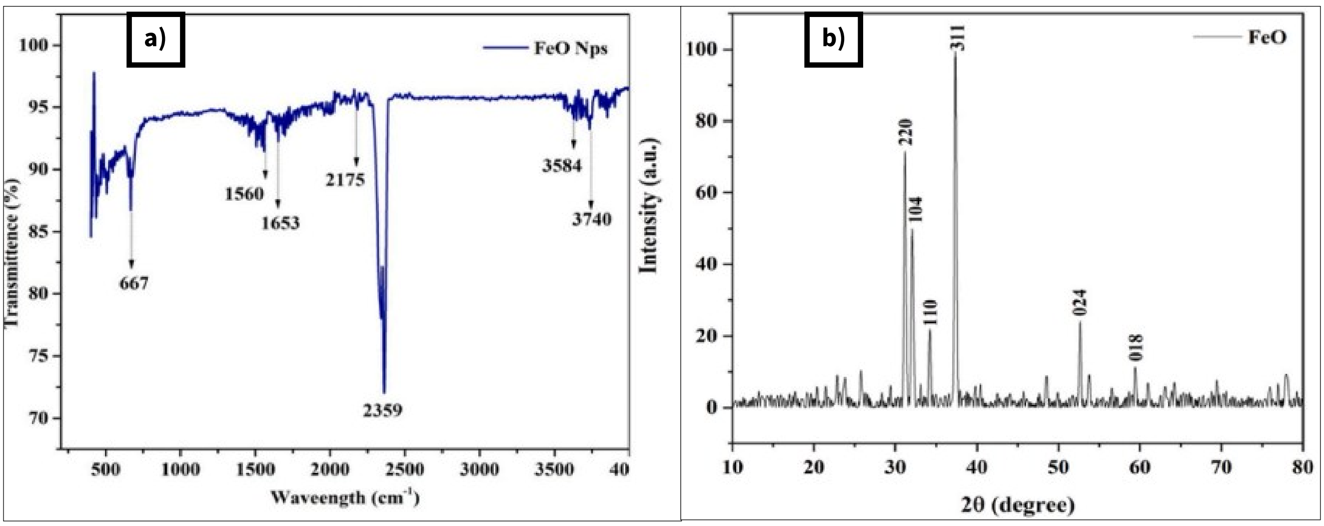

Fig. 3. The chemical composition of Fe nanoparticles. (a) Fourier transform infrared spectroscopy and (b) X-ray diffraction analysis (39).

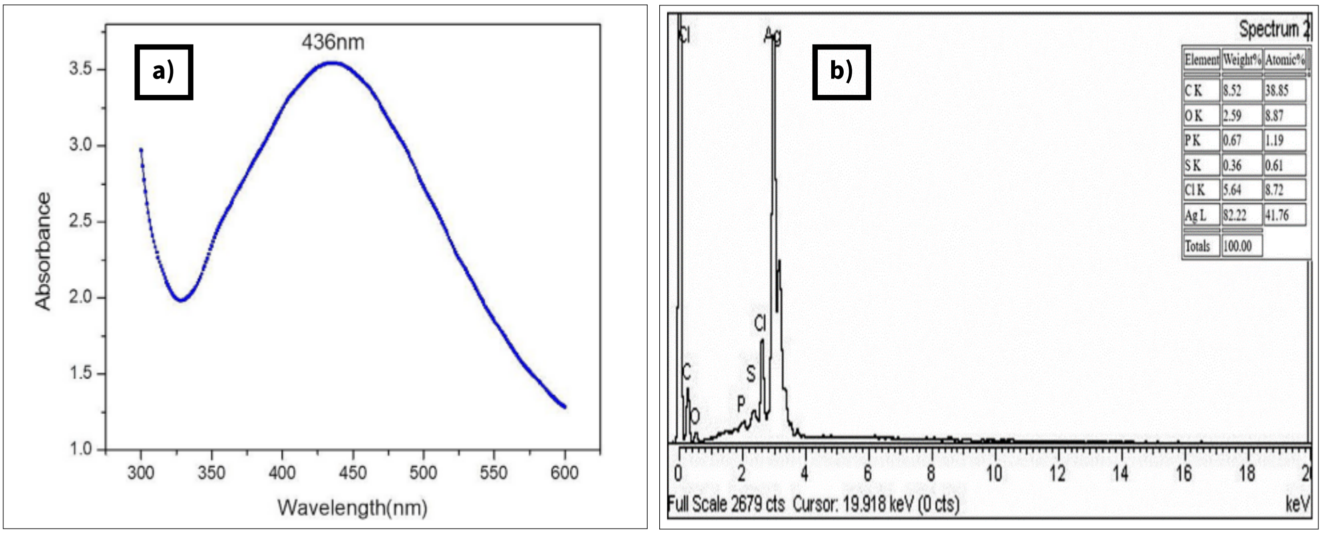

Fig. 4. Shows the UV-Vis spectroscopy and Energy dispersive X-ray analysis of silver nanoparticles (40). (a) UV-Vis spectroscopy; (b) Energy dispersive X-ray profile.

most common characterization techniques used to verify the chemical and physical properties of the prepared nanoparticles

The application of Au, Fe and Ag nanoparticles in antibacterial and cytotoxicity studies

Au, Fe and Ag nanoparticles exhibit unique physicochemical properties that enable a wide range of biological and medical applications. Au nanoparticles are highly biocompatible and easily functionalized, making them valuable in drug delivery, photothermal cancer therapy, biosensing, imaging and rapid diagnostics due to their strong surface plasmon resonance. Fe oxide nanoparticles possess superparamagnetic behavior, enabling their use as MRI contrast agents, magnetically guided drug-delivery systems and mediators of magnetic hyperthermia in cancer treatment, in addition to applications in tissue engineering and immunomagnetic cell separation. Silver nanoparticles, renowned for their potent antimicrobial and antiviral properties, are widely utilized in wound dressings, infection-resistant medical device coatings, antiviral formulations and cancer therapy through the induction of oxidative stress. Together, Au, Fe and Ag nanoparticles represent a versatile platform in modern biomedicine, contributing to improved diagnostics, targeted therapeutics, infection control and regenerative medicine. Due to their strong antibacterial and antiviral properties, Ag are frequently utilized in antiviral formulations, wound dressings, infection-resistant medical device coatings and cancer treatments by inducing oxidative stress. In contemporary biomedicine, Au, Fe and Ag nanoparticles collectively constitute a flexible platform that supports enhanced diagnostics, targeted treatments, infection prevention and regenerative medicine (26–30).

The present study primarily focused on the application of Au, Fe and Ag nanoparticles against bacterial pathogens and cell lines to review their effect as antibacterial agents and cytotoxicity, respectively. As shown in Table 2, these metal nanoparticles were evaluated for their antimicrobial activity against a wide range of bacterial pathogens, including *Escherichia coli* (31), *Brevibacterium linens* (33), *Bacillus subtilis*, *Candida albicans* (35), *Bacillus marisflavi* (36), *Staphylococcus aureus* (49), etc. Moreover, the prepared metal nanoparticles show a significant effect against them. The table also includes the cells that were used to evaluate whether these nanoparticles are toxic to them. And demonstrate that it can be safe and utilized in the biological and medical fields.

Due to their unique physicochemical and biological characteristics, gold, iron and silver nanoparticles play a crucial role in cytotoxicity and antibacterial research. The most decisive antibacterial action is exhibited by silver nanoparticles, which are highly effective against both Gram-positive and Gram-negative bacteria by rupturing cell membranes, producing reactive oxygen species (ROS) and inhibiting DNA replication. Iron oxide nanoparticles demonstrate mild antibacterial effects by producing ROS and damaging cell membranes. When functionalized with antimicrobial compounds or exposed to light for photothermal death, gold nanoparticles acquire high bactericidal and cytotoxic properties despite having reduced intrinsic antibacterial activity (61–67). AgNPs frequently exhibit dose-dependent toxicity against both microbial and mammalian cells in cytotoxicity experiments. In contrast, FeNPs exhibit comparatively low toxicity and strong biocompatibility and AuNPs are typically benign but can become cytotoxic depending on their surface chemistry, size and shape. In general, these nanoparticles are being investigated extensively for the creation of next-generation biomedical materials, controlled cytotoxicity in cancer research and safe antimicrobial treatments (68–72).

The role of Au, Fe and Ag nanoparticles in wastewater treatment applications

Water pollution from industrial effluents, agricultural runoffs and domestic discharge is a major global problem. Conventional treatment methods generally cannot effectively remove trace pollutants, pathogens and recalcitrant organic compounds (73, 74). Nanotechnology has recently emerged as a powerful approach to addressing global wastewater contamination challenges. Among the various nanomaterials, Au, Fe and AgNPs have attracted significant attention due to their unique physicochemical properties, including high surface-area-to-volume ratios, elevated reactivity and tunable surface chemistry (75). These features enable efficient adsorption, catalysis and degradation of pollutants. Furthermore, Fe-, Ag- and Au-based nanoparticles exhibit distinct functional advantages such as magnetic recoverability, catalytic activity and antimicrobial effects which make them highly promising for advanced wastewater treatment applications (76–78).

Iron-based nanoparticles (Fe-NPs)

Iron-based nanoparticles (Fe, Fe_2O_3, Fe_3O_4) are extensively used for adsorption, degradation and fixation of heavy metals, dyes and organic pollutants by mechanisms including redox reaction, Fenton-

Table 2. Au, Fe and Ag nanoparticles in antibacterial and cytotoxicity studies

No	Bacteria	Cell	Characterize	Size of particles	Shape	Ref
1	*Escherichia coli*	/	SEM, XPS, XRD and uv-vis	8-20 nm	Spherical	(31)
2	/	/	SEM, XRD and Uv- vis	20-100 nm	Nonwoven 3D network structures	(32)
3	*Brevibacterium linens*	/	HR-TEM, SEM, EDS, XRD, FTIR and UV- vis	10-75 nm	Rectangular, spherical, hexagonal with smooth edges	(33)
4	/	/	Uv-vis, XRD, SEM, AFM and FTIR	75- 130 nm	Spherical and irregular aggregates	(34)
5	*Bacillus subtilis*, *E. coli* and *Candida albicans*	/	TEM, FTIR, XRD, SEM, EDX and Uv-vis	21-57 nm	Spherical	(35)
6	*Bacillus marisflavi*	/	XRD, SEM, EDX, DLS, TEM, FTIR and Uv-vis	12-30 nm	Spherical	(36)
7	/	/	XRD, FTIR, TEM, SEM, DLS and uv-vis	18-70 nm	Spherical	(37)
8	/	/	TEM, XRD, XPS,	10-20 nm	Spherical	(38)
9	*Staphylococcus aureus* and *E. coli*	/	XRD, SEM, EDX, TEM and uv-vis	10-100 nm	Spherical	(39)
10	/	/	XRD, SEM, EDX and FTIR	Below 100nm	Microfibers	(40)
11	/	/	TEM, EDS, XRD, FTIR and uv-vis	20-160 nm	Irregular clusters	(41)
12	/	/	SEM, EDX, XRD, AFM and uv-vis	28-66 nm	Variable shapes and in agglomerated form	(42)
13	/	/	Uv- vis, FTIR and SEM	50-400 nm	Spherical	(43)
14	*S. aureus, B. subtilis*, *E. coli* and *Pseudomonas aeruginosa*	/	XRD, DLS, TEM and uv -vis	13-25 nm	Hexagonal	(44)
15	*P. aeruginosa*, *E. coli*, *S. aureus* and *B. subtilis*	/	Uv-vis and AFM	8 nm	Spherical	(45)
16	*S. aurous, B. cereus, E. coli* and *P. aeruginosa*	/	SEM, EDX, DLS and FTIR	30 nm	Spherical	(46)
17	*Klebsiella, E.coli, Pseudomonas* spp., *S. aureus*	Hela, BHK-21 and Vero cell line	FTIR, XRD, SEM and uv-vis	22 nm	Uniform in nature and get agglomerated in some cases	(47)
18	*K. pneumoniae, E. coli* and *S. aureus*	/	SEM, EDX, FTIR, DLS, TEM and uv- vis	20-80 nm	Nanorod like	(48)
19	*S. aureus* and *E. coli*	/	FTIR, SEM and XRD	14-23 nm	Spherical, nano-rods and some agglomeration	(49)
20	/	MDCK and Caki-2 cells	FTIR, XRD, SEM, EDX, UV-vis and TEM	39 nm	Spherical	(50)
21	/	/	Uv-vis, XRD, SEM, EDX and TEM	10-25 nm	Spherical with some irregular particles	(51)
22	*E. coli*, *Salmonella typhi*, *P. aeruginosa* and *Shigella boydii*	Human cervical cancer cells (HeLA)	XRD, EDX, FTIR, TEM and uv-vis	10-25 nm	Spherical	(52)
23	/	MCF7 human breast cancer cells	Uv-vis, XRD, FTIR and TEM	12-24 nm	Spherical as well as pseudo-spherical in form	(53)
24	*E. coli*	/	Uv-vis, Raman spectra, TEM and FTIR	2.35 nm	Semispherical to large oblongated particles,	(54)
25	*P. acnes* and *S. epidermidis*	/	Uv-vis, XRD, TEM, FTIR, SEM and DLS	50-60 nm	Nearly irregular to spherical.	(55)
26	*P. aeruginosa*	/	DLS, SEM and FTIR	35 nm	Spherical	(56)
27	*E. coli*, *P. aeruginosa, A. niger, A. fumigatus* and *A. flavus*	/	FTIR, UV-vis and TEM	75 nm	Spherical	(57)
28	*E. coli*, *P. aeruginosam, S. aureus* and *B. cereus*	/	UV–Vis, FTIR, XRD, SEM, EDX and TEM	16-20 nm	Spherical	(58)
29	*S. aureus*, *B. subtilis*, *E. coli* and *P. Aeruginosa*	Prostate cancer cell line and breast cancer cell line	Uv-vis, FTIR, XRD, SEM, EDX and TEM	8- 40 nm	Spherical	(59)
30	*S. aureus*, *S. typhi*, *E. coli*, *Candida albicans*, *Trichoderma viride*, *Penicillium notatum* and *Aspergillus niger*	/	UV-vis, FTIR and AFM	84 nm	Hexagonal	(60)

like reaction and magnetic separation respectively. Their high reducing capabilities and magnetic recoverability result in efficient and even environmentally friendly materials which are cost-effective for large volume-scale applications (79, 80). Iron-nano-based nanomaterials, such as Fe_3O_4, Fe_2O_3, FeOOH and Zero-Valent Iron (nZVI), are utilized for their adsorption and active materials for catalyst of many applications, as in Table 1.

Iron nanoparticles (FeNPs) are regarded as among the most promising nanomaterials for wastewater treatment due to their cost -effectiveness, environmental compatibility and strong reactivity toward a wide range of contaminants (82). They efficiently remove heavy metals such as arsenic (As), chromium (Cr) and lead (Pb) through reduction and adsorption processes, while organic pollutants including dyes, pesticides and chlorinated hydrocarbons are degraded via redox and catalytic mechanisms (83—7).

Zero-valent iron nanoparticles (nZVI), provide a high surface-area-to-volume ratio that enhances electron transfer and accelerates pollutant degradation and they can be synthesized from inexpensive precursors through green or bio-based methods, contributing to their sustainability and low cost (88).

Despite these advantages, Fe-NPs face key limitations, most notably agglomeration which reduces their reactive surface area and oxidation, which converts Fe^0 into less reactive oxides such as Fe_2O_3 or Fe_3O_4, thereby diminishing their mobility and efficiency in aquatic systems. To overcome these challenges, stabilization strategies such as polymeric, surfactant and carbon-based coatings have been developed to improve their dispersion, resistance to oxidation and overall long-term performance (88, 89). (Table 3).

Silver-based nanoparticles (AgNPs)

AgNPs are particularly advantageous for antimicrobial and disinfectant activities. They inactivate bacteria, viruses and fungi in wastewater by releasing Ag^+ ions and generating ROS, which can disrupt cell membranes and metabolic processes (90, 91). Moreover, AgNPs also help in the photocatalytic photo degradation of organic pollutants, through photo catalyst addition as shown in Table 4. AgNPs exhibit exceptional antibacterial and antifungal properties, making them ideal for disinfection and biological contamination control.

AgNPs are among the most extensively studied nanomaterials for wastewater treatment due to their exceptional antimicrobial, catalytic and optical properties. Their strong disinfection ability comes from several mechanisms, including breaking cell membranes, producing ROS and interacting with DNA and proteins. These mechanisms allow them to effectively inactivate a wide variety of bacteria, viruses and fungi (92).

Besides their antimicrobial properties, AgNPs also serve as effective photocatalysts under visible and UV light. They enable the breakdown of organic pollutants, including dyes, pesticides and pharmaceutical residues, by facilitating electron transfer and decreasing the recombination of photo-generated charge carriers. This enhances their usefulness in advanced oxidation processes (AOPs) for water purification. Despite these strengths, AgNPs face limitations related to high material cost, susceptibility to aggregation and oxidation and concerns about ecological toxicity due to the release of Ag^+ ions, which may pose risks to aquatic organisms and environmental health (93, 94).

To overcome these issues, composite systems incorporating AgNPs with stable and low-cost supports such as TiO_2, graphene, activated carbon and silica have been developed to improve dispersion, stability, photocatalytic efficiency and reusability, while minimizing free silver release (95, 96). Overall, Ag-based nanocomposites represent a promising pathway for next-generation wastewater treatment technologies, offering a balance between strong disinfection capabilities, pollutant degradation efficiency and improved environmental safety.

Gold-based nanoparticles (AuNPs)

Gold nanoparticles, particularly Au-citrate NPs, are known for their stability and catalytic properties in removing organic pollutants. AuNPs, although more expensive, provide enhanced stability and catalytic efficiency (97). Especially in photocatalytic degradation of persistent organic pollutants, they are very well-suited for sensing applications for detecting trace contaminants as shown in Table 5. Their tunable optical and surface properties can be incorporated into hybrid nanocomposites as an effective strategy to enhance performance.

AuNPs exhibit excellent chemical stability, catalytic efficiency and reusability, making them attractive candidates for advanced wastewater treatment applications. Their strong resistance to oxidation and aggregation enables them to retain catalytic activity even under harsh environmental conditions (104). However, their

Table 3. Comparative summary of iron nanoparticle compounds for wastewater treatment applications

Compound/ Symbol	Chemical Type	Mechanism / Function	Target Pollutants	Notes	Ref
Fe_3O_4 (Magnetite NPs)	Magnetic iron oxide	Adsorption and Fenton-like catalysis	Pb^{2+}, Cd^{2+}, Cr (VI), dyes	Easy magnetic separation	(81,82)
γ-Fe_2O_3 (Maghemite)	Ferric oxide	Adsorption and photocatalysis	As(V), Cu^{2+}, MB dye	High chemical stability	(83)
α-Fe_2O_3 (Hematite)	Ferric oxide	Visible-light photocatalysis	Phenol, dyes	Cheap, abundant, non-magnetic	(79)
nZVI (Fe^0)	Zero-valent iron	Reductive degradation	Cr (VI), NO_3^-, TCE	High activity, easily oxidized	(80)

Table 4. Comparative summary of silver nanoparticle compounds for wastewater treatment applications

Nanomaterial	Mechanism	Target Pollutants	Removal Efficiency	Notes	Ref
AgNPs	Antibacterial and photocatalytic	*Pathogenic bacteria*, *E. coli*, dyes	95–99 % microbial removal	High cost; risk of toxicity	(73)
Ag–TiO_2 composite	Photocatalytic oxidation	Dyes, pharmaceuticals	90–98 % degradation	Enhanced under UV/visible light	(98)
Ag–TiO_2 nanoparticles	photocatalytic oxidation	dyes	-	High material cost, reduced activity in real wastewater	(99)
AgNPs	Water purification	Pure water permeability, salt rejection, dye removal and antifouling performance	67 %	Potential membrane fouling, environmental and regulatory concerns	(100)

Table 5. Comparative summary of gold nanoparticle compounds for wastewater treatment applications

Nanomaterial	Mechanism	Target Pollutants	Removal Efficiency	Notes	Ref
Au-citrate NPs	Adsorption and catalysis	Dyes, heavy metals	85–95 %	High stability, but expensive	(97)
Au–Fe_3O_4 hybrid	Catalytic and magnetic	Dyes, phenols	90–96 %	Easily recovered magnetically	(101)
graphene oxide AuNPs	Adsorption	Dye	-	High Cost, Adsorption Capacity is Not High Compared to Other Adsorbents	(102)
AuNPs	Catalytically active	Azo-dye reduction		High Stability, High Catalytic Efficiency, Scalability Concerns and Mechanistic Understanding is Limited	(103)

large-scale application remains limited due to the high cost of gold and the complexity of nanoparticle synthesis (105).

To enhance feasibility, recent studies have focused on developing hybrid or composite systems in which Au-NPs are integrated with cost-effective support materials such as iron oxides, graphene, TiO_2 and zeolites. These composites improve catalytic activity, recoverability and dispersion while reducing overall cost, thereby enhancing environmental and economic suitability (106–108). When combined with Fe- and Ag-based nanoparticles, AuNPs contribute to a complementary treatment strategy in which FeNPs provide strong adsorption and redox performance, AgNPs offer effective disinfection and photocatalysis and AuNPs supply high catalytic stability (109—11).

This synergistic approach enhances removal efficiency for heavy metals, dyes, pathogens and persistent organic pollutants. Despite these advantages, challenges such as nanoparticle aggregation, post-treatment recovery, toxicity risks and high manufacturing costs remain significant. To address these limitations, green synthesis routes, biocompatible surface coatings and magnetically recoverable nanocomposites are increasingly emphasized as essential strategies for enabling safe and sustainable large-scale implementation of nanotechnology-based wastewater treatment.

Comparison of Fe, Ag and Au nanoparticles

Iron-based nanoparticles have high adsorption, redox and Fenton-like properties and are well-suited for removing heavy metals, dyes and nitrates. The material's magnetic nature enables their easy recovery; however, oxidation and aggregation may impair performance. Nevertheless, their low cost and eco-friendliness render them applicable for large-scale use (112–114).

AgNPs have effective antimicrobial and photocatalytic activity, degrading dyes and pathogens by Ag^+ ion release and ROS generation. Working with TiO_2 or ZnO improves the performance. However, the high cost and toxicity concerns of these substances limit large-scale applications. AuNPs possess remarkable stability and catalytic efficiency in degrading persistent pollutants. They are also oxidation-resistant and can be reused in hybrid systems, but high production costs limit their application at scale (115–117).

In conclusion, as demonstrated in Table 6 and Fig. 5, Fe nanoparticles appear to be the most suitable for large-scale pollutant removal due to their low cost and strong redox properties. Ag nanoparticles exhibit strong antimicrobial activity and effective pathogen removal, whereas Au nanoparticles are highly efficient in catalytic degradation and sensing but are constrained by economic factors. The interaction of these nanoparticles with composite/hybrid approaches may generate synergistic effects and in the long-term yield more efficient and sustainable wastewater purification.

Summary

Nanotechnology offers a unique and effective approach to addressing the global challenge of wastewater pollution. Among the different nanomaterials studied for this task, iron (Fe), silver (Ag) and gold (Au) nanoparticles show remarkable potential with unique physicochemical and catalytic activity. Compared to traditional methods, iron nanoparticles are particularly promising for scale-up treatment systems due to their low cost, high reactivity and magnetic recoverability, making them effective for removing heavy metals and dyes through redox and adsorption processes.

Although gold nanoparticles are generally costly, they stand out for their high catalytic stability, adjustable surface properties and plasmonic photocatalytic activity, making them very promising for the targeted breakdown of complex organic pollutants and pollutant detection

Silver nanoparticles have developed to exhibit outstanding antimicrobial and photocatalytic properties and allow disinfection of pathogens and degradation of organic pollutants. The Ag⁺ ions produced and the ROS that they generate are known to be active for microbial inactivation. Although gold nanoparticles are generally costly, they stand out for their high catalytic stability, adjustable surface properties and plasmonic photocatalytic activity, making them very promising for the targeted breakdown of complex organic pollutants and pollutant detection. Thus, there are diverse benefits of the different nanoparticle types for wastewater:

- FeNPs: Perfect for the large amounts of metals and organic impurities removed.
- AgNPs: More suitable for microbial and sterilizing purposes.

Table 6. Comparison of Fe, Ag and Au nanoparticles for wastewater treatment applications

Parameter	Fe-based NPs	Ag-based NPs	Au-based NPs
Main pollutants treated	Heavy metals, dyes, nitrates	Bacteria, dyes	Dyes, metals
Removal efficiency	85–99 %	90–99 %	85–95 %
Cost	Low	Moderate to high	High
Environmental risk	Low (eco-friendly)	Moderate (toxic at high dose)	Low
Reusability	High (especially magnetic types)	Moderate	High
Practical application level	High (widely tested)	Medium (pilot scale)	Low (lab scale)

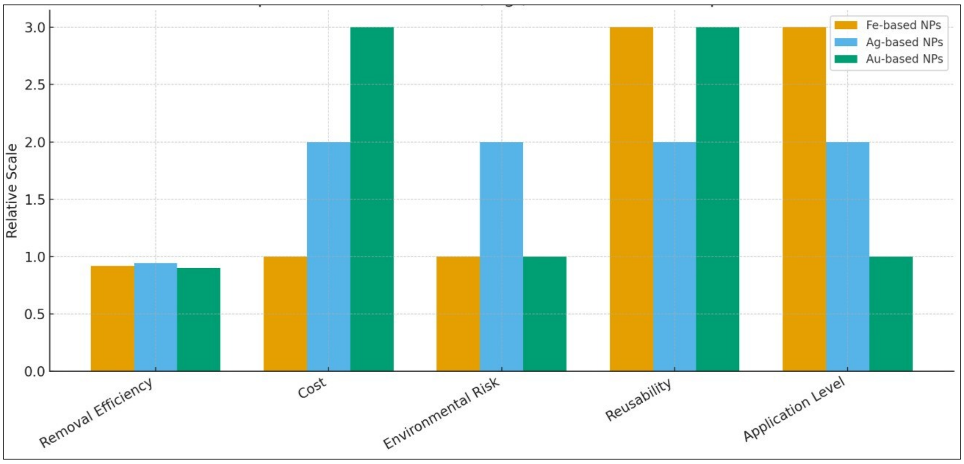

Fig. 5. Comparative performance chart of Fe-, Ag- and Au-based nanoparticles.

- AuNPs: Super-efficient for catalytic degradation and sensing.

Conclusion

In conclusion, the unique physicochemical and biological properties of Au, Fe and Ag nanoparticles make them highly versatile materials with great potential for environmental cleanup and biomedical uses. Chemical, physical, biological, or green manufacturing techniques all have a significant impact on the size, shape, surface chemistry and stability of nanoparticles, which, in turn, affect their antibacterial, cytotoxic and catalytic properties. TEM, SEM, XRD, UV-Vis spectroscopy, FTIR, DLS and zeta potential are examples of characterization techniques crucial for understanding and managing these characteristics. Au, Fe and Ag nanoparticles have effective antibacterial properties in biomedical applications through processes such as biomolecular interference, reactive oxygen species production and membrane rupture. The integration of Fe-, Ag- and Au-based nanoparticles into hybrid or composite systems offers a promising pathway for achieving highly efficient and multifunctional wastewater treatment, as these combinations enable synergistic interactions among adsorption, redox processes, catalytic activity and antimicrobial effects. For the practical and sustainable application of such nanotechnologies at larger scales, future research should prioritize. Advancing magnetically recoverable and durable nanocomposites that support continuous operation and lower maintenance costs in real wastewater treatment systems. By addressing these challenges, nanoparticle-based technologies particularly those involving Fe-, Ag- and Au-NPs can evolve into robust, scalable and eco-friendly solutions capable of supporting next-generation wastewater treatment infrastructure. Moreover, our suggestions for future research can include: (i) the development of magnetically recoverable and durable nanocomposites for efficient reuse, (ii) comprehensive toxicity and life-cycle assessments to ensure environmental safety and (iii) optimization of green synthesis methods with validation in real wastewater systems to support scalable and sustainable applications.

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Authors' contributions

MAAH designed the study, performed the experiments, prepared the manuscript and assisted with data analysis. MM interpreted the data, wrote the paper, supervised the experiments, revised the manuscript and provided significant suggestions to improve the assessment. Moreover MA, collected data and make the table outline. All authors read and approved the final manuscript.

Compliance with ethical standards

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