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A Review of Iron polyphenol green nanomaterials and their environmental applications

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Abstract **- Iron–polyphenol green nanomaterials have evolved as a promising class of sustainable materials due to its low toxicity, ecofriendly, and low-cost characteristics. This review investigates the synthesis, characterization, and prospective environmental implications of iron–plant polyphenol complexes, with precise prominence on their function as green nanomaterials. Polyphenols developed from plant sources such phenolic acids act as natural antioxidant, and stabilizing agents, allowing formation of iron-based nanostructures under mild and environment friendly conditions. The review also enlightens the basic mechanisms governing iron–polyphenol complexation, including redox interactions, coordination reactions, and antioxidant activity, which mutually control material stability and reactivity.**

Moreover, the review also imparts special focus on environmental applications, especially in wastewater treatments, where such nanomaterials validate high efficacy for remediation from heavy metals, dyes, nutrients, and even emerging contaminants through adsorption, and redox transformation. Their versatility goes beyond water treatment to beneficial agricultural applications, where iron–polyphenol complexes enhance bioavailability of micronutrient, soil health, and plant stress resistance. Furthermore, the intrinsic antimicrobial properties of polyphenols, synergistically improves by iron-mediated reactive oxygen species production, are reviewed in the context of bacterial resistance by damaging their cells.

Conclusively, this review highlights the prospectives of iron–polyphenol green nanomaterials as economical, biodegradable, and scalable substitutes to conventional synthetic nanomaterials. Current challenges, knowledge gaps, and future research directions related to material optimization, environmental fate, and large-scale implementation are also discussed to facilitate their transition from laboratory research to real-world applications.

Keywords - Adsorption, green synthesis, iron polyphenol, pollutant removal, antimicrobial activity.

1. INTRODUCTION

In the twenty-first century, the world's population is confronted with serious water quality challenges. Despite the fact that water is the most vital natural resource, just 1% of it is suitable for human use [1]. Approximately 1.1 billion people do not have access to safe drinking water, according to the World Health Organization (WHO, 2015). The water issue is exacerbated by poor water management, the generation of a massive volume of hazardous waste, and its improper disposal [2]. The inevitability of wastewater treatment reinforces the need to develop sustainable treatment options. Pollutants released in wastewater can be hazardous to aquatic life and able to change the condition of the aquatic ecosystem [3]. Various approaches for purifying wastewater have been developed, such as sedimentation, membrane filtration, flotation, precipitation, adsorption, ion exchange coagulation, oxidation, etc. [4–6]. Among them, adsorption is a much simpler and attractive procedure in comparison to other methods due to its high efficiency and ease of handling. Besides, it shows good efficiency in low concentrations of pollutants. Traditional methods for removing contaminants from wastewater are not cost-effective, particularly at low pollutant concentrations [7]. Moreover, adsorption has also been in practice for decades in the treatment of wastewater from distinct sources [8–10]. Additional benefits include the recovery of pure metal for recycling and the reuse of the adsorbent [11]. However, conventional adsorbents are chemically modified, susceptible to secondary effects, and expensive. Therefore, in the current scenario, there is an obvious need for sustainable, cost-effective, energy-efficient, and green adsorbent. This review is an attempt towards contributing to the water treatment process using eco-friendly efficient bio-adsorbent.

Adsorption by biomaterials, commonly known as biosorption, is a popular approach where different parts of plants, dry leaves, shoot powder, barks, agricultural wastes, fruit shells, and a variety of other biological materials have all been investigated over the years (Figure.1) (Table 1.1).

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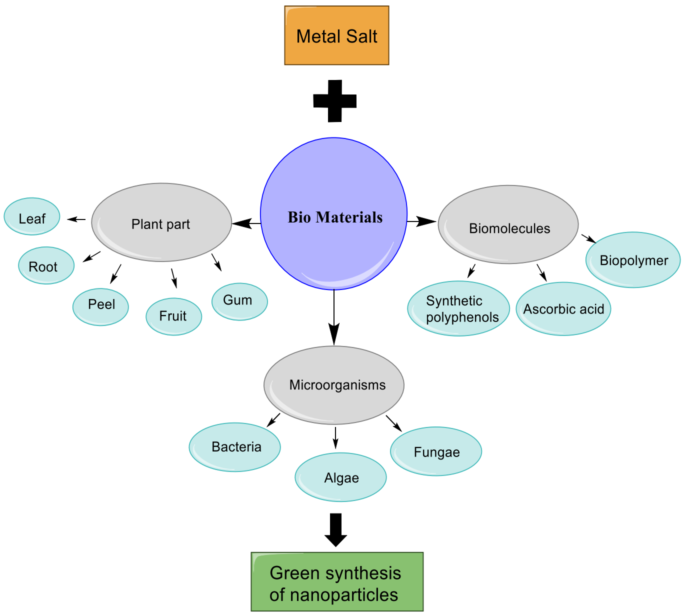

Figure 1. Schematic representation of green synthesis of nanoparticles

Bio-adsorbents have been the subject of a recent flurry of research articles due to their simple process, biodegradability, low cost, nontoxic, ecofriendly, and year-round availability. Some of the selected bio-absorbents used for the removal of different kinds of pollutants from wastewater are enlisted in the following table.

Table 1.1. Selected list of different bio-adsorbent used in pollutant removal.

Adsorbent	Pollutant	References
Rice hull ash	Lead (II)	[1]
NaOH treated rice husk	Malachite green	[2]
Wheat bran	Chromium (VI)	[3]
Ocimum americanum L. seed pods	Chromium (VI)	[4]
Aegle marmelos correa (Bael fruit)	Chromium (VI)	[5]
Okra, pumpkin, grape, and squash	Copper ions	[6]
Sugarcane bagasse	Cu^{2+}, Cd^{2+}, and Pb^{2+}	[7]
Sugarcane bagasse	Rhodamine B (RhB) and Basic Blue 9	[8]
Iron oxyhydroxide NP coated rice husk	Fluoride	[9]
Azadirachta indica (Neem)	Lead (II)	[10]
Rambutan peel based activated carbon	Remazol Brilliant Blue R	[11]
Phoenix tree leaf powder	Methylene blue	[12]
Pea peels	Bismarck brown	[13]
Coconut husk	Mercury (Hg^0)	[14]
Activated carbon from coconut coil	Methylene blue	[15]
Eichhornia crassipes (Water hyacinth)	Phosphorus	[16]
Water hyacinth was modified by citric acid	Ni (II), Cu (II), and Cr (VI)	[17]
Bamboo dust carbon	Methylene blue	[18]
Tea extract mediated nanoparticles	Malachite green, rhodamine B	[19]

It can be concluded from the above table that different parts of plants, different agro-waste, water hyacinth, etc., in dry or powder form, in some modified form, after converting in charcoal were used for adsorption of different heavy metals, dyes, and other pollutants present in wastewater. However, in many literatures activated charcoal from different biomaterials were used for water treatment purposes but, energy consumption and air pollution is an adverse side of it. The use of biomaterial's extract and different precursor salts for the synthesis of different metal-ligand complexes is another well-known area of study regarding environmental application and environmental chemistry.

The presence of polyphenol in different parts of plants like root [29], shoot, leaves, seed [30], bulk, etc., acts as a ligand and makes complexation in the presence of different precursor metal salts. The specific components that cause plant-mediated metal complex synthesis and the mechanism of action are still unknown. Different secondary metabolites such as flavonoids, polyphenols, terpenoids, and heterocyclic compounds have been suggested to react with metal salts and produce plant mediated-metal complex [31,32]. Different polyphenols like gallic acid, ellagic acid, quercetin catechol derivatives etc., present in plant extracts are soluble in water, and some organic solvents react with precursor iron salt solutions (Figure 2).

Polyphenols are chemically interesting due to their redox activity, which is the origin of their function as an antioxidant. Polyphenols are structurally diverse, and their reactivity depends on pH. The size distribution of these synthesized materials usually belongs within nano ranges [28,33,34]. Due to their high surface-to-volume ratio, nanoparticles are well known for their application in water treatment.

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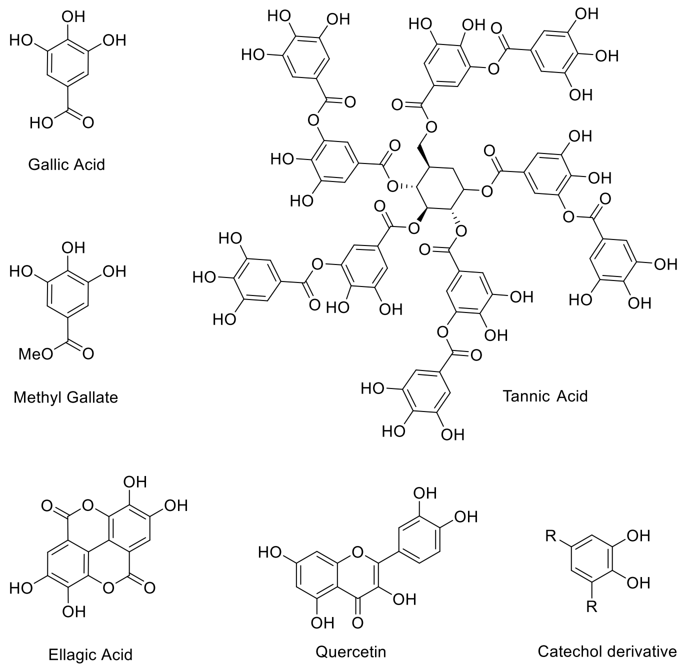

Figure 2. Structure of selected plant polyphenols.

Hence, these materials are also well known as green synthesized nanoparticles. The small size ranges of the materials possess increased surface area, which helps in the adsorption of pollutants due to increments of active sites. Moreover, the use of plant materials for the green synthesis of nanoparticles is useful for its cost-effectiveness, bulk production, and effective reproducibility process. Table 1.2 represents various plant parts utilized in different literature for synthesizing metal-based nanomaterials.

The production of green nanoparticles provides numerous advantages over traditional methods that include no energy requirement, significant affordability, and eco-friendliness as no toxic byproducts are produced [35]. The benefit of green produced nanoparticles synthesis is that they do not require synthetic reducing agents, which are detrimental to the environment. Additional benefits of green synthesis over traditional ones include the possibility of bulk scale production, no requirement of external conditions such as high pressure and energy [36].

Table 1.2. Literature of plant-mediated synthesis of the nanoparticles.

Plant name	Plant part	Metal salt	Application	References
Benjamina	Leaf	Silver	Cadmium	[20]
Trigonella foenum-graecum	Leaf	Silver	Reactive blue 19 and Reactive yellow 186	[21]
Terminalia bellerica kernel	Fruit	Silver	Methyl orange, Eosin yellow	[22]
Palm tree (*Phoenix dactylifera*)	Leaf	Copper–silver	Methylene blue	[23]
Mussaenda glabrata	Leaf	Gold and silver	Rhodamine B, methyl orange	[24]
Stemona tuberosa Lour		Gold	4-nitrophenol, methylene blue, methyl orange and methyl red	[25]
Lagerstroemia speciosa	Leaf	Gold	methyl orange, bromophenol blue and bromocresol green, and 4-nitropheno	[26]
Hibiscus sabdariffa	Flower	Copper	Nitrate	[27]
Citrofortunella microcarpa	Leaf	Copper	Rhodamin B	[28]
Moringa oleifera	Leaf	Iron	Nitrate removal,	[29]
Dodonaea viscosa	Leaf	Iron	Antimicrobial	[30]
Laurus nobilis L	Leaf	Iron	Antimicrobial against *Listeria monocytogenes* bacterium.	[31]
Carica papaya	Leaf	Iron	Remazol yellow RR dye degradation	[32]
Tea	Leaf	Iron	Malachite green, rhodamine B and methylene blue dye removal	[19]
Simmondsia chinensis	Seed	Iron	Fluoride removal	[33]
Nettle and Thyme	Leaf	Iron	Cephalexin (CEX) antibiotic removal	[34]
Azadirachta indica	Leaf	Iron	ammonia nitrogen, COD	[35]
Eucalyptus teretiornis,	Leaf	Iron	Dye removal	[36]
Eucalyptus globules	Leaf	Iron	Chromium	[37]
oolong tea	Leaf	Iron	Malachite green	[38]
Green tea		Iron	Methylene blue and methyl orange	[39]
Lantana camara	Leaf	Iron	Ni (II)	[40]
Oak, mulberry and cherry	Leaf	Iron	Arsenic (III), Chromium	[41]
Eichhornia crassipes, *Lantana camara* and *Mimosa pudica*	Leaf	Iron	Nitrate and phosphate	[42]
Vaccinium corymbosum	Shoot and leaf	Iron	Arsenic	[43]
Tea extract	Leaf	Iron	Bromothymol blue	[44]

Table 1.2 summarizes the utilization of several plant species for the synthesis of plant-mediated metal nano complexes. Different precursor metal salts like silver, gold, copper, nickel, and iron were used for complexation purposes. Among them, some metal salts are quite costly, which makes the synthesized materials expensive, and some have some toxic effects on the environment. However, the use of iron salt for synthesis makes the material cost-effective and environmentally friendly. Apart from it, iron is a common earth element also very essential for

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the growth of the living body. Iron forms strong bonds with the phenolic –OH group of the polyphenols to form a complex. Iron after complexation generally prefers the Fe (III) oxidation state, but in a mixture, some amount of Fe (II) could also be present [60-61].

Polyphenols can react with iron in various ways depending on pH, iron oxidation state, metal-ligand ratio, and oxygen present. Depending upon pH, polyphenols and polyphenolic-metal complexes can be varied structurally, show different coordination modes [60–62]. Iron binds to polyphenol due to the antioxidant actions of polyphenols [64, 71-73].

2. APPLICATION OF IRON-PLANT POLYPHENOL COMPLEXES IN WASTEWATER TREATMENT

2.1 Wastewater Treatment

Zhu et al. (2018) used green tea extract was utilized for the synthesis of zero-valent iron/Cu nanoparticle synthesis at N_2 atmosphere and employed for the removal of Cr (VI) from aqueous solutions [74]. At pH 5, zero-valent iron/Cu nanoparticles were capable of 94.7 % removal of 5 mg/L of Cr (VI) solution. The material was characterized by FESEM, FTIR, and PXRD (peak is unclear, polyphenol not measured, no iron-polyphenol ratio). Pan et al. (2019) used peanut skin for iron-based nanoparticles synthesis purposes [75]. This study described the core-shell structure of nano complex with Fe (0) in the core, surrounded by the biomolecule layer. The material was characterized using PXRD, FTIR, XPS, and UV-spectroscopy. Moreover, SEM images showed agglomeration of the particle. Materials showed 100% removal of 10 mg/L of Cr (VI) at pH 4.7 and 2 g/L of dose. Similarly, Jin et al. (2018) synthesized zero-valent iron nanoparticles using eucalyptus leaf extract and applied for chromium removal [76]. The experiment was executed with 10 mg/L of chromium solution, at pH 4, nanoparticle dose of 1.4 g/L, 30°C. Results showed 86% removal of total chromium.

Ehrampoush et al. (2015) utilized tangerine peel extract, which acted as a stabilizing agent for the synthesis of iron oxide nanoparticles by co-precipitation method and utilized for cadmium adsorption [77]. The average size of the particles in DLS was 200 nm. Moreover, the removal experiment showed 88% removal of 20 mg/L of Cd at 4 pH, with a material dose of 4 g/L.

Machado et al. (2017) utilized the oak leaves to synthesize nanoscale zero-valent iron and analyzed the degradation of a popular antibiotic and amoxicillin in wastewater [78]. They studied the degradation of 100% of amoxicillin occurred at 95 min of contact time in an aqueous solution with amoxicillin and nanoparticle in the ratio of 1:15. Apart from these, Lantana camara fruit extract was used by Nithya et al. (2018) for the synthesis of iron oxide nanoparticles and applied for the removal of Ni (II) [34]. With the dose of the nanoparticle of 1.2 g/L, 99% removal of 100 mg/L of the solution was observed at pH 7. Manquián-Cerda et al. (2017) employed the plant leaves and shoots extract of *Vaccinium Corymbosum* to synthesize iron nanoparticles and apply them for arsenate removal [58]. Nanoparticles were characterized using TEM, SEM (52 nm), BET, PXRD. They reported that the maximum removal of 76% of 200 mg/L arsenates was observed at pH 4, and 120 min of reaction time. Furthermore, Sajadi et al. (2016) utilized the plant seeds of Silybum marianum L. for the synthesis of copper-supported iron nanoparticles and applied them against nitrobenzene reduction [79]. Materials were characterized by XRD, TEM, EDS, and UV–vis spectroscopy. Maximum removal of 96% was observed for 1 mmol of concentration at 90 min of reaction time. The following tables show the summary of plant-mediated iron-nano complexes synthesized by using different plants, characterized, and applied to remove pollutants from wastewater.

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Table 1.3. Use of plant-mediated nanoparticles in wastewater treatment.

Plant name	Application	Condition	Removal or uptake	Comment	References
Green tea, Eucalyptus leaf	Nitrate	20 mg/L, 1g dose	50 and 35%	Total phenol not measured. EDS only. PXRD peak not clear	[45]
Nephrolepis auriculata	Chromium (VI)	50 mg/L of	90%	XPS, EDS, Fe^{+3}, Fe^{+2}, Fe^{0} Nitrogen atmosphere for synthesis. The dose is not clear.	[46]
Citrus maxima peels	Chromium (VI)	100 mg/L, 90 min,	99%	TEM, EDS, XPS, IR, DLS. Nanoparticles in solution phase. The dose of material is not clear. Removal was not checked with varying conditions.	[47]
Oak, mulberry and cherry NPs	Arsenic (III),		300 mg/g 200 mg/g and 250 mg/g	Polyphenol not measured, no characterization for the state of iron. Claim Zero valent NPs	[41]
Tangerine peel extract	Cadmium	4 pH, 4 g/L of dose, 20 mg/L of Cd	88%	No polyphenol estimation. SEM, DLS only. In removal, no triplicates	[48]
Nettle and Thyme leaf	Cephalexin antibiotic	25 mg/L, 0.1g dose	80%	Powder XRD, peaks of different state of Fe were there. Claim Zero valent NPs	[34]
Cupressus sempervirens leaf	Methyl orange dye	25 mg/L, with H_2O_2, 1 g/L dose	95%	Polyphenol not measured. PXRD	[49]
Hibiscus flower petals	Rodamine B		20 mg/g	Synthesis and characterization not cleared, EDS done. Claim Zero valent NPs	[50]
Eucalyptus leaf	Acid black 194 COD, N		71% and 84% removal	Iron-Polyphenol complex	[51]
Oolong tea	Malachite green	50 mg/L conc, 0.01g dose, in 40min.	73%	EDS, PXRD. NP in solution phase	[38]
Iron-polyphenol with Eucalyptus and 2 other plants	Acid red 94 and MB	2000 mg/L initial conc. 24hr contact time.	Uptake is 463 mg/g for acid red and 64 mg/g for MB	IR, TEM only. NPs in solution used. Not in powder form. Dose and other parameters not clear	[52]
Iron-polyphenol with Eucalyptus leaf	Acid black 194	1300 mg/L of 2000 mg/L initial conc. 24h contact time. pH 3-9	> 80% removal.	UV, IR NPs in solution used. Not in powder form. Dose and other parameters not clear	[36]
Tea leaf	Malachite green (MG), methylene blue (MB), and rhodamine B (RB)	0.01 g of dose, 50 mg/L initial conc.	Uptake of 190.3 mg/g, 186.93 mg/g and 182.4 mg/g, respective	IR, XPS, zeta potential. Only kinetics study	[19]
Fe-zero with Guava leaf	MB	50 mg/L conc, 2.4g/L dose.	> 94% removal	UV-TEM-IR. Claim Zero valent NPs	[53]
Tea leaf-Iron, NZVI activated carbon comparison	Real textile water	Initial- 350 mg/L conc. dose 0.7g. pH 5 for NZVI, 8 for AC, and 7 for green nano.	72% removal for AC, 85% removal for green nano. And 71% for nZVI	XRD, SEM, EDX, different modeling. UV peak not mentioned.	[54]
Fe_3O_4 coated-tea polyphenol	MB removal	3.5 mg/L conc, dose 1g/L, pH >7.	Uptake 5mg/g	ESI mass, PXRD, raman, VSM, BET surface area 126	[55]

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It was observed that no confined protocol was followed for synthesis purposes. In different reports, various kinds of synthesis processes were used. Thus, there exists a scarcity of knowledge regarding detailed analysis of zero-valent iron, irrespective of results reported in various literature. In some literature, the formation of zero-valent iron was claimed without proper characterization of the materials. However, in some literature, iron complexes were separated using centrifugation and applied as a powder form. Whereas, according to some other experimental results, materials were present in the suspension phase. So to say, basically, in all the studies, the efficiency of iron-polyphenol complexes in pollutant removal was studied.

2.2 Application in Agriculture

Iron is an important element for plant growth, photosynthesis capacities, as well as different biochemical processes. It is also crucial for the structure of chloroplasts, as well as Fe-S group is essential to ensure electron flow in the thylakoid membrane [90]. Iron also has an important role in synthesizing chl-b from chl-a [91]. In different literature, iron-based nanomaterials improved plant growth in terms of biomass, root-shoot growth, photosynthesis capacity, productivity, etc. [92,93]. However, some literature reported the negative impact on the plants, like the accumulation of iron nanoparticles in the root surface and cause the suppression of water uptake, suppression on growth, induce stress, etc. [94–96]. Table 1.4. Summarizes different studies on the effect of iron-based nanoparticles on plant species.

Table 1.4. Positive and negative effects of different metal complexes on different plant species.

Materials	**Species**	**Analysis**	**Comment**	**References**
Iron oxide NPs	Lemna minor	No. of leaves, dry weight, Fe accumulation in the root, chlorophyll, Lipid peroxidation were measured.	At high concentration, chlorophyll content decrease, MDA production increased. Showed toxicity on plant and kill plants within 7 days in all concentration range.	[56]
Iron (III) oxide NPs	*Vigna radiata*	Dry biomass, root-shoot growth, Fe and As analysis, proline test, H_2O_2 content, total antioxidant capacity, SEM, etc., were measured.	The effect of Seedlings raised in AsO_4^{3-} and Fe_2O_3-NPs, and in combined conditions were evaluated in this study. AsO_4^{3-} reduces the seedling growth. Fe_2O_3-NPs showed resistance to arsenic toxicity.	[57]
Micro and nano-sized iron	*Lepidium sativum, Sinapis alba*, and *Sorghum saccharatum*	Germination index, elongation, biomass, microscopic observation was checked.	No significant phytotoxicity effects could be detected. Increased seedling length and biomass production were observed.	[58]
Fe_3O_4 nanoparticle	Cucumber and lettuce	Root elongation, germination index, relative seed germination was checked.	Decrease in root growth and germination index.	[59]
Zero-valent iron	Cattail and hybrid poplars plant species	Root-shoot weight, length were measured. FESEM, EDX, TEM were also checked.	The result showed the toxic effect on cattail species at >200mg/L of concentration. While at a lower concentration, it enhances plants growth.	[60]
FeO_x NPs	*Lactuca sativa*	Germination test, root shoot length	1mg/L dose helped in germination and growth. However, 20mg/L dose suppressed the germination of seeds.	[61]
Zero-valent iron nanoparticle	*Oryza sativa* cv	Germination test, growth, hydrolytic enzyme activities, antioxidant, proline, chlorophyll.	Increased root-shoot length, biomass, and chlorophyll. absence of membrane damage, decrease in proline content.	[62]
Zero-valent iron nanoparticle	Peanut	Germination test, growth, TEM	40 and 80 µmol/L of dose better of growth of plants.	[63]

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In the above table, it could be seen that iron complexes were able to show positive effects by increasing the plants' productivity, growth, and biomass. On the other hand, some literature showed the negative influence of iron complexes on plants, such as the deposition of iron nanoparticles in the root surface, which reduces the water intake, affects growth rate, and induces stress.

2.3 Antimicrobial Activity

The application of iron complexes on nanomaterials has significant potential in the inhibition of various diseases causing bacteria and fungi. Although the mechanism of these metal nano compounds, antimicrobial properties are yet to be known. A number of the proposed mechanisms of antimicrobial activities have been suggested, including breakage of the cell membrane, damage of DNA, etc. Lee et al. (2008) studied the effect of zero-valent iron on E. Coli and studied the severe physical disruption of membranes which could have induced oxidative stress and showed the high antimicrobial effects of dissolved iron [104]. However, the absence of a harmful effect of nZVI on the species was observed by Stefaniuk et al. (2016), and further growth of Gram-positive bacteria was found [105]. The following table shows the summary of the inhibition effect of iron polyphenol complexes on different microbes.

Table 1.5. Antimicrobial activity of iron nanoparticles.

Materials	Species	Comments	References
Iron oxide NPs with *Cynometra ramiflora* leaf extract	*E. oli* and *S. epidermidis*	Kirby-Bauer diffusion assay with 70 µL of material. (dose is not clearly mentioned). The exact area of ZOI is not mentioned.	[64]
Gallic-Aluminium and gallic-iron complex	*E. oli*	Only iron-gallic acid complex is effective in showing inhibition. ZOI of the iron-gallic complex is 12.00 ± 0.25 mm with 50µL of genotoxic dose.	[65]
Iron oxide NPs with tannic acid	*Trichothecium roseum, Cladosporium herbarum, Penicillium chrysogenum, Alternaria alternata,* and *Aspergillus niger.*	With 0.5 mg/ml dose of iron nano, the ZOI of the different fungi are as follows: *T. roseum*, (22 mm) *C. erbarum*, (18 mm) *P. hrysogenum,(*28 mm) *A. alternate* (21 mm) and A. niger (26 mm).	[66]
Iron oxide magnetic NPs with *Argemone mexicana* L. leaf extract	*E. coli, P. mirabilis* and *B. subtilis*	8 mm ZOI with 12.5 µg/disc of dose.	[67]
Iron oxide NPs	*Staphylococcus aureus*, *Escherichia coli*, and *Pseudomonas aeruginosa*	With a dose of 0.15 mg/mL of NPs, the ZOI against S. aureus, E. coli, and P. aeruginosa is 29,26,28 mm.	[68]
Iron oxide NPs	*Bacillus subtilis* and *E. coli*	Showed antimicrobial activity at > 50 µM. relatively at high concentrations	[69]
Fe_3O_4-NPs	*Bacillus cereus* and *Klebsiella pneumoniae*	With 5 µg/mL of MIC, against *K. pneumoniae* and *B. cereus* showed 26 mm and 22 mm zone of inhibitions, respectively. MBC for these strains was observed at 40 µg/mL of Fe3O4-NPs, showing 40–50% loss in viable bacterial cells and 80 µg/mL of concentration exhibiting 90–99% loss.	[70]

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This table summarizes the capabilities of different types of iron nano-complexed against various microorganisms to check their inhibition. Different kinds of methods were used for the estimation of the antimicrobial activity of iron-based materials. The phytochemicals are capable of showing antimicrobial activity and fight against several pathogenic diseases [113]. Literature showed the formation of reactive oxygen species (ROS) that breaks the DNA stand and also causes the death of the cells [111]. The mechanism of inhibition varies from species to species. Considering the small size of the iron complex, it can easily penetrate the bacterial membrane due to the adhesion and deposition of the materials, as a result of which cytolysis occurs [114].

3. CONCLUSION

This review consolidates current knowledge on iron–plant polyphenol complexes as an emerging category of green nanomaterials with significant environmental relevance. Iron strongly binds with phenolic –OH of plant's polyphenols. The unique coordination chemistry between iron ions and naturally occurring polyphenols enables the formation of stable, multifunctional nanostructures using environmentally benign synthesis routes. These materials combination of iron with the antioxidant, and antimicrobial properties of polyphenols, resulting in synergistic performance across diverse environmental applications.

In wastewater treatment, iron-polyphenol nanomaterials have demonstrated remarkable effectiveness in removing a wide range of contaminants, including heavy metals, synthetic dyes, nutrients, and emerging pollutants. Beyond water remediation, their application in agriculture highlights their role in enhancing iron bioavailability, improving soil fertility, and promoting sustainable crop production while minimizing environmental risks associated with synthetic agrochemicals. Due to the production of different reactive oxygen species, such as hydroxyl radicals, singlet oxygen, etc., which induce stress and cause resistance against bacteria by damaging the cell. Therefore, the antimicrobial activity of these complexes provides additional value for controlling pathogenic microorganisms in environmental and agricultural systems.

Despite these promising attributes, challenges remain related to long-term stability, reusability, mechanistic understanding under complex environmental conditions, and scalability of production. Future research should focus on standardizing synthesis protocols, assessing environmental fate and ecotoxicity, and integrating life-cycle and techno-economic assessments. Addressing these gaps will be crucial for translating ironâ€“polyphenol green nanomaterials from experimental studies to practical, large-scale environmental solutions. Overall, these materials represent a compelling pathway toward sustainable nanotechnology-driven environmental management.

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