

1. Introduction

Over the last few years, an increasing number of nanomaterials have been developed specifically for environmental applications, and they have been used to remediate contaminated soil and groundwater from hazardous waste present in them. The materials used for the remediation of pollutants are to be ensured that they do not become pollutants after being implemented. Thus, biodegradable materials are an excellent choice for the application. Biodegradable materials offer an eco-friendly and safer alternative for the effective treatment of pollutants while increasing the rate of acceptance of modern technology [1].

A high surface area-to-volume ratio coupled with remarkable reactive sites contribute to the high reactivity of nanomaterials. Low efficiencies derived from off-targeting are nullified using new technologies which rely on target-specific capture of contaminants. Surfaces of nanoengineered materials which are modified through physical and chemical methods serve to combat the challenges faced in removal of water contamination. NPs offer appealing features such as biodegradability, nontoxicity, cost-effective synthesis and
maintenance, target-specific capture, recyclability, and the potential for recovery after use, which supports their extensive use despite demerits that include recovery costs, toxicity of metallic NPs and their by-products, and requirement of special preparation techniques owing to their limited stability under normal conditions [2].

Nanomaterials should be developed with a thorough comprehension of the fabrication processes, performance optimization strategies, and material platforms. Long term, this approach could assist us in addressing environmental issues on a larger scale. Extracts obtained from different parts of plants naturally act as capping agent, and this property can be exploited to synthesize metallic NPs under Phytonanotechnology [3].

Phytonanotechnology is a discipline that governs the use of plant-based or plant-mediated biomaterials in the synthesis of metallic NPs for the detection of lethal pathogens in those facilities and to assess the degree of risk imposed by other factors to the environment. The infallibility and eco-friendliness of these processes have contributed to its industrial usage [4].

Lead has been depended on for various industrial purposes that has resulted in large-scale water contamination and significant health hazards in many parts of the world. Biologically synthesized magnetic NPs of iron oxide (II, III) (Fe₃O₄) were designed for the removal of metal from a solution (aqueous). The leaf extract of Moringa oleifera was specifically used and confirmed the size of the NP in the range of 60-100 nm. The synthesized NPs achieved 94.08% removal of lead within 60 min of contact time [5].

Cobalt oxide NPs have been reported to be eco-friendly, facile, nontoxic, and highly resistant to corrosion and oxidation. The NPs were synthesized using the fruit extract of Vitis rotundifolia using coprecipitation. With a reaction time of 150 min and a degradation potential of 98%, the acid blue 74 dye was chosen as a standard for the measurement of photocatalytic activity of the NPs [6].

There are continuous efforts in research to develop NPs from different sources. An emerging branch of nanotechnology seeks to synthesize NPs from natural sources such as bacteria and fungi. The green synthesis of such NPs relies on secondary metabolite extracts, the mycelial surface of fungi, and bacterial culture growth rate extracts of the plant which are the main accessible mechanisms in synthesis. The topography of the land area also demands the action of appropriate in situ and ex situ technologies. In situ remediation can reach inaccessible areas such as crevices and aquifers which eliminates the need for other expensive operations [7].

The main objective of this review is to understand how Phytonanotechnology is utilized in the bioremediation of wastewater. The content pertains exclusively to bioremediation of pathogens, organic compounds, dyes, and heavy metals (Figure 1).

2. Role of Phytonanotechnology in Removal of Water Contamination

A pioneering approach in response to the growing concern of water contamination is the utility of green synthesized nanomaterials which possess superior chemical reactivity, greater mechanical durability, higher surface area-to-volume ratio, and absorption-adsorption potentials which facilitate the removal of effluents along the lines of heavy metals, organic compounds, dyes, and pathogens discharged consequently as a ramification of domestic, commercial, and industrial activities. The upcoming sections engage each of these categories centrally and focus on the commission of novel methods and biomaterials for their removal from such resources or reservoirs.

2.1. Role of Phytonanotechnology for Removal of Heavy Metals

Different industries release effluents in the form of toxic heavy metals which find applications in research labs and in production plants, into wastewater. The prominent use of these metals in a wide range has been a cause of water pollution, and it is increasing at a rapid rate. Many metals like chromium, arsenic, copper, iron, and cadmium are found in water bodies.

Iron NPs were prepared from barberry leaves extract, and a ferric chloride solution of 0.1 M was prepared. Weight percentages of carbon and oxygen were obtained as 48.4 and 44.5% (estimate), respectively, via EDS, and its map scanning shows uniform distribution of Fe and Cr. The elemental speciation of GT-nFe surfaces and its mapping prior to Cr removal and after was expedited using XPS, which showed peak results at 712.4, 719.1, and 726.1 eV, assigned to Fe 2p3/2, Fe0, and Fe 2p1/2, sequentially. The acidic pH condition gives high efficiency of Cr removal by the NPs with the rate of 99.7% at a pH of 4 within 6 h along with the dosage of 0.5 g/l−0.12 g/l in acidic conditions. The 100% removal of Cr went down to 17.7% when the initial concentrations of Cr were increased to 200 mgl⁻¹. With higher temperature, there was high absorbance and the isotherm models of Freundlich and Langmuir were employed which described the Cr (VI) adsorption [8].

The NPs obtained from Konjac glucomannan were at a size range of 5.98 ± 2.02 nm, and to detect the presence of metal particles, EDS was employed along with Pd NPs with 3.0 keV as a strong peak. The EDS mapping also determined the elemental composition of NPs. The Pd NPs had a size range of 3.2 to 10.0 nm and was confirmed via DLS, and the XRD spectra showed the crystalline structure. TEM analysis shows the particles as spherical and worm-like shapes. During the removal of Cr, the absorption peak was seen at 350 nm which was estimated because of the LMCT with an overall of 93% of Cr reduction at 45°C along with Azo dyes reduction; the entire mechanism followed the pseudo-first-order [9].

Green tea leaf extracts were used for the preparation of Fe-NPs, and those were implemented for the Cr removal from the wastewater. The SEM results showed that the NPs have an irregular spherical shape with a diameter of range 30 to 100 nm in size. The before and after reaction results of XPS spectra showed that GT-nFe exhibited characteristic peaks after exposure to Cr. Higher removal efficiencies were found in acidic medium and high temperatures, and 100% removal efficiency was attained with the dosage of 0.12 g l⁻¹ but with limited presence of Cr (VI) concentration and mechanism [10].
The removal of chromium was achieved using iron NPs harnessed from straw waste powder. They were dried at 80°C forming a solid powder, and the precursor was incubated in a nitrogen atmosphere for 120 min at 800°C for calcination and obtaining hierarchically porous carbon (HPC) by heating them at the rate of 3°C min⁻¹. Similarly, most of the NPs were prepared and applied with the use of heat, biomaterial, and radiations. SEM analysis gave the morphological analysis of the NPs, and in the reactivity test, Ni doping results to the increase in Cr removal. The higher dosage did not favor the removal capacity of NPs, 0.5 g L⁻¹.

A fresh banana waste peduncle (BWP) was obtained, and spherical AgNPs 25 nm in size on average as per TEM images were fabricated which facilitated Cr removal. The absorption peak was seen at 3453 cm⁻¹ via FTIR for BWP extract. The photoreduction of Cr(VI) was monitored by the decay around 350 nm and was reduced by a minimal amount of 9% but increased with the presence of strong oxidants, and the same NPs were also effective for the removal of MB dye and Cr along with antimicrobial activity [12].

Similarly, petroleum wastewater has contaminants like Cr and Cd; and Ag-NPs are synthesized from the walnut fruit for its remediation. The NPs average size was 47.4nm which was estimated via TEM. They also showed a round shape without any aggregation with 41.2eV of zeta potential conforming a negative charge of NPs. The absorption increased along with the increase in temperature until 35°C and no further change above it. The total absorption capacity was seen as 81.3% for Cr and 88.1% for Cd ions when petroleum wastewater was used. At pH2, photocatalytic reduction of Cr was observed at full absorption potential and followed pseudo-second order model of kinetics [13].

Silver NPs were also obtained from Benjamina leaves extract termed as Ficus benjamina leaves extract (FBLE). A formula as % removal = ¥ Co – Ce/Co × 100 was used to estimate the total removal of Cd (II) from polluted water. The presence of proteins and polyphenols was confirmed by FTIR spectral images. Different concentrations and conditions were considered, and the highest Cd (II) removal % was recorded at 40 min, and the SEM results showed that the Ag-NPs have a dendritic structure [14].

Green tea extracts were also used for the removal of Sb contaminants, and the NPs had a smooth surface which was seen and observed via SEM. The BET analysis showed the pore-like structure of NPs which were in a range of 10–100nm. The removal efficiency of Sb decreased from 66.5 to 36.8% with the increase in the Sb contaminants in the solution from 0.5 to 2 mg L⁻¹ but also increased with an increase in pH, along with the GO-Fe/Ni dose and temperature. The pseudo-first-level model of kinetics best explained the oxidation of Sb(III) to Sb(V) [15].

Rice residue powder was used for the removal of arsenic, and the biochar obtained from it was labelled as MBC (magnetic biochar) of which 10 g was later added to ethanol-water solution (60%, v/v) and to 2 ml of ammonia (28%). ZBC were obtained when a solution of ZrOCl₂.8H₂O was added to the entire solution and left at RT for 24 h. Both MBC and ZBC were at a size of 200nm. Their crystalline structures were obtained by use of XRD. After the introduction of the NPs in the MBC, the capacity for As removal was observed to be increased; also, the SBET showed that ZBC had a more porous structure than MBC. Even zero-valent iron NPs (ZVI NPs) are gaining huge demand in the water remediation methods because of their characterization of heavy metal removal. It also possesses some antimicrobial properties [16].

Black tea (BT) was prepared by heating tea powder in distilled water, and the extract was later vacuum-filtered. FeSO₄ solution with 0.1 molarity was added to the extract at a ratio of 1:2. The polyphenol groups present act as reducing and capping agents by forming complexes with Fe metal ions producing zero-valent metals which forms ZVI NPs which were then later collected by using vacuum filtration. In the ongoing work, we modify the efficiency NPs by using gamma radiation and its effects on the structural properties of NPs, and hence, the removal efficiency.
of Cu$^{2+}$ ions goes up to 97% at pH5. The removal efficiency decreased linearly with an increasing temperature which is a typical behavior for exothermic adsorption processes. The absorbent is relatively stable as the removal capacity was 85% even after six regeneration cycles. The NPs also possess antibacterial activity which was effective against *S. aureus*, *S. aureus*, and *E. coli* [17].

Similarly, *Ziziphus jujuba* leaves extract was used to obtain zinc oxide NPs which were used for the removal of Pb and dyes like MO and MB by absorption mechanism. The absorption peaks at 3421 cm$^{-1}$, 2925 cm$^{-1}$, 1637 cm$^{-1}$, and 1384 cm$^{-1}$ (3421 cm$^{-1}$ was strongest) using FTIR were observed, whereas Bragg’s reflection using XRD for ZnO NPs were recorded at $2\theta = 31.73^\circ$, 34.38°, and 36.20° with an average of 15 nm NPs as obtained from TEM. ZnO NPs because of their small particle sizes and overall high surface area decreased the removal efficiency when contrasted with G ZnO NPs. GMW ZnO NPs rapidly removed all toxins present within the sample in 30 min, pH 5.6 at 25°C [18].

Silver NPs were obtained using *Piliostigma thonningii* leaf extract. Time, pH, temperature, and total AgNO$_3$ content were maintained in a controlled environment to obtain the contaminants’ removal efficiencies. An absorbance maximum was observed at 415 nm when incubated for 60 min at an optimum pH of 6.5 and temperature of 65°C, and the concentration of AgNO$_3$ was 1.25 mM. The NPs were spherical with a size range of 50–114 nm with a crystalline structure. The elemental synthesis of sliver was at 2.60 keV which was confirmed by EDX, and the capping agent was suggested to be hydroxyl (OH) group. The NPs also showed heavy metal removal activity in laboratory simulated wastewater [19].

*Simarouba glauca* leaf extract was used to obtain copper ferrite NPs for Pb removal. These metal oxide NPs are very cost-efficient as they can be recovered at the end of the reaction and can be reused up to three times and also possess antimicrobial properties. The average crystallite size of CuFe$_2$O$_4$ is 9 nm which was confirmed by XRD. The absorption mechanism was observed with different dosage levels from 0.025 g to 0.1 g/100 ml in 10 mg/l lead solution, and the analysis showed that after a certain dosage, there was no increase in absorption at pH 6 with 80% Pb removal efficiency [20].

In another work, Au-NPs with particle size between 22 and 54 nm were synthesized using a reducing sample of lemon juice extract. FTIR results indicate the electrostatic interaction between Au-NPs and oxygen atoms in C=O due to the lone pairs. Even though the main study focused on nickel removal, the results showed 100% remediation for Pb. These NPs were used on Wilkerson Filters to confirm the results [21].

Dried seed extracts of *Moringa oleifera* is used to synthesize Fe-NPs for Pb(II) removal from water. Varied concentrations of the NPs showed different removal efficiencies for different contaminants; for the removal of heavy metals like zinc, scandium, silver, lead, and mercury, the precipitate was formed in 30 min. The optimized amount for the experiment was 0.5 mM AgNO$_3$ and the SEM image showed that the NPs are of size 4 nm with an even shape and spherical surface. The AFM results showed that the NPs have different sizes and a crystalline structure was observed from XRD and TGA results [22].

2.2. Role of Phytonanotechnology for Removal of Organic Compounds. Triclosan (TCS) is an organic compound that is a huge threat as a water pollutant and can cause various health diseases. Bimetallic iron/nickel NPs were used for the removal of the same. A solution of dried 30 g *eucalyptus* leaves and 500 ml of deionized water was prepared with 1 h incubation at 80°C. The extract obtained was filtered, and reagents were added; later, the suspension was vacuum filtered, rinsed with ethanol, and freeze-dried. In the experiment along with the TCS, the Cu removal was also achieved. The sample was taken in amber centrifuges and was added with Fe/Ni NPs and filtered using 0.22 μm PTFE membrane filters. With the following formula $R% = C_0 – C_1 /C_0 \times 100$, the removal efficiency was calculated. SEM determined that the average size of NPs was polydisperser (60–85 nm) before reaction and was increased slightly after the reaction with TCS and Cu, and the EDS spectrum depicted the change in contents of Fe from 11.8% to 15.4% and Ni from 0.7% to 0.4%. FTIR spectra showed that the attributable characters were at peak and retained in the entire reaction. The XPS analysis showed that the NPs became more corroded after exposure to the contaminants. The mix contaminant removal was higher than the single contaminant removal rate with a constant pH at 6, and with higher dosage of NPs, the Cu removal is increased. The optimal removal was at 30°C [23].

The leaf extract was prepared from *Ipomoea carnea* leaves with dry seeds of *Brassica alba* which were both powdered. Both the seed powder and the leaf extract were each boiled in 100 ml of deionized sterile water for 60 min, and the NP obtained from this extract was used to remove an organic compound, chlorfenapyr, from the water. The NPs could be cubical, circular, triangular, hexagonal, or rod-shaped, with a size range of 6.27–21.23 nm. The crystalline structure was observed via SAED. When some other NPs were added with Fe/Ni NPs and treated, rinsed with ethanol, and freeze-dried. In the experiment along with the TCS, the Cu removal was also achieved. The sample was taken in amber centrifuges and was added with Fe/Ni NPs and filtered using 0.22 μm PTFE membrane filters. With the following formula $R% = C_0 – C_1 /C_0 \times 100$, the removal efficiency was calculated. SEM determined that the average size of NPs was polydisperser (60–85 nm) before reaction and was increased slightly after the reaction with TCS and Cu, and the EDS spectrum depicted the change in contents of Fe from 11.8% to 15.4% and Ni from 0.7% to 0.4%. FTIR spectra showed that the attributable characters were at peak and retained in the entire reaction. The XPS analysis showed that the NPs became more corroded after exposure to the contaminants. The mix contaminant removal was higher than the single contaminant removal rate with a constant pH at 6, and with higher dosage of NPs, the Cu removal is increased. The optimal removal was at 30°C [23].

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For the removal of polyaromatic hydrocarbons (PAHs), copper NPs have been synthesized from plants extracts. Cu-Cs were extracted from *Coriandrum sativum*, and a total of 12 batches of experiments were performed to obtain precise results, and the synthesized NPs were applied as biosorbents. Overall, copper NPs had a removal capacity of 98.07%. In the FTIR analysis, the samples were recorded in the range of 1600–4000 cm$^{-1}$ at a resolution of 4 cm. Through FTIR results, the best peaks are shown at 470 cm (C O), 424 cm, 413 cm, and 402 cm, respectively. FTIR results indicated that metals have an absorption limit of 300–600 cm$^{-1}$ which also confirmed the synthesis of NPs [25].
In the same manner, the removal of phosphate is important, and *Sapindus plant* extract was used to synthesize ZrO$_2$ NO which was used as an absorbent for removal of phosphate. The XDR results showed the average size of NPs as 10.91 nm; FE-SEM results gave the porous and irregular structure of NPs. FTIR and EDX showed a peak at 2,352.2 cm$^{-1}$ which was observed for the first time in the after-adsorption spectrum, and it was estimated to be observed because of the phosphate absorbance with its removal to be in the range of 80.9%-90.3% [26].

Ag-NPs were synthesized from the peel extract of *Citrus maxima* at room temperature. A stable NPs formation was confirmed via SPR (surface plasmon resonance). The presence of silver metal was confirmed by peaks observed at 2.9 and 3.1 KeV via EDS, and a crystalline structure was observed along with face-centric cubic (FCC) lattice in XDR analysis. Ag NPs size ranged from 4 to 11 nm with a spherical shape which was observed via TEM. Naringin, naringin, and hesperidine were also present with a functional group as O-H along with flavonoid rings was observed under FTIR spectra. Alkaline conditions favor the yield of NPs; hence, a pH of 12 obtained NPs of size 8.6 nm. The ICP-MS revealed the yield of Ag NPs to be about 99%, and the NPs also depicted excellent catalytic activity by degradation of 4-nitrophenol (a pollutant); the NP also had antioxidant properties with anti-bacterial properties too [27].

In another study, Ag NPs were obtained using *Acalypha hispida* extract which acted as a mild reducing agent with stabilizing properties. The dried plant was heated in water, and the extract produced was refrigerated for further use. The Ag/MgO nanocomposites were formed, which was confirmed using TEM analysis with an average size of 23 nm and possessing a spherical structure which were immobilized on the MgO surface. This green method has short reaction times with high yields and clean conditions. When NaBH$_4$ was used in water along with Ag/MgO, a high reduction was observed. TEM, XRD, EDS, and FE-SEM techniques were applied to confirm the formation of Ag/MgO. Due to immobilization, the NPs were successfully reduced six times [28].

Another set of Ag NPs was synthesized using the *Terminalia bellirica* Kernel extract. The NPs showed an average size of 29.6 nm as obtained using TEM. The synthesized silver NPs showed a catalytic reduction of many organic pollutants with a high reduction of 4-nitrophenol than any other organic pollutants. The samples were incubated for 60 min, and a total of 87.0% of 4-nitrophenol was reduced. Kinetic study confirmed that the pseudo-first-order of kinetics was followed. For the NPs, an ANN model was developed and implemented which estimated the catalytic performance of these NPs [29].

The *M. burkeana* plant extracts were taken to synthesize zinc. The sulfsioxazole (SIZ) rate of degradation helped us to evaluate ZnFe$_2$O$_4$ photolytic activity under UV light irradiation, and a 10-ppm aqueous solution (100 ml) was dispersed. FTIR spectra showed calcination of ZnFe2O4 in 2 h of a time period with a temperature of 700°C. The XDR showed the crystalline structure displaying 2θ diffraction peaks at 53.993°, 62.411°, 35.602°, 53.993°, 49.401°, and 57.560°. The SEM results showed that the NPs had a rod-like structure with a size ranging from 30 to 70 nm. Zn, Fe, and O elements were detected under EDX confirming the formation of NPs. The EPR spectrum detected the para magnetism of the NPs. The optimum pH was 12, and the total removal of sulfsioxazole was 67% in 120 min following the pseudo-second order [30].

Au-Ag NPs were synthesized using *L. inermis* seed extract which had a spherical and irregular shape. To get Au-Ag BNPs, 5 ml of 1 mM HAuCl$_4$ and AgNO$_3$ were taken in a ratio of 1:1. The UV-Vis spectra showed a strong SPR center formation at 537 nm which confirms the formation of Au-Ag BNPs. FTIR detected the presence of functional groups (alcohols/phenols, carboxyl, alkaline, and hydroxyl) and aromatic rings. XDR detected the crystalline structure of the NPs with HR-TEM determining the size average size of 32 nm of the NPs, and SAED patterns indicated FCC crystal structure formation in NPs. The donor BH$_4$ transports its electron to the acceptor 4-nitrophenol, and the entire remediation is dependent on this reduction process. Also, the time taken for reduction was 20 min for 50 ml, 10 min for 100 ml, and 3 min for 150 ml, which indicates that with the decrease in time, the reduction output was also decreased. The entire reaction had its rate constant as 0.5297, 0.2608, and 0.0631 min$^{-1}$ following pseudo-first-order kinetics [31].

A nonsteroidal antiinflammatory drug (NSAID) is a hazardous substance that is being released in water, and some prominently found substances are ibuprofen (Ibu), naproxen (Nap), and diclofenac (Dic), and for the removal of the same green synthesized Cu, nanoabsorbents were used in presence of *Tilia* leaf extract. The XRD results show the diffraction peaks at 2θ ¼ 35, 50.50, and 74.21 with the unit cell having an FCC structure with the UV-Vis analysis of Cu NPs which showed a plasmon peak of at 562 nm. TEM results confirmed well-dispersed spherical and semispherical NPs (4.7 to 17.4 nm). It is understood that the remediation of NSAIDs is entirely pH-dependent with maximum removal efficiency at 4.5 pH. An increase in dosage of Cu NPs increases the removal efficiency, and a similar efficiency increase was seen with the increase in NSAIDs concentrations. The maximum removal of Dic, Ibu, and Nap were found to be 91.4%, 74.4%, and 86.9%, respectively, when set at ideal conditions of 298 K temperature, for 60 min with the dosage of 10 mg Cu NPs under the pH of 4.5 [32].

The *Calotropis gigantea* (CG) flower extracts and dry *Pithecellobium dulce* seed extracts were analyzed for the study. The strong absorption peaks disappeared at the 300 to 350 nm region confirming the polydisperser ZVIN. The bands were seen highest at the range of 3359–3361 cm$^{-1}$ in FTIR analysis which was estimated to be there because of the phenolic groups present for the reduction to Fe$^0$ from Fe$^{3+}$. The XRD determined the crystalline structure NPs, and the peaks obtained at 2θ of 45° and 65° in XRD results were because of the Fe$_3$O$_4$ presence. The XDR also showed the crystalline structure of the NPs. The SEM analysis showed NPs with a spherical shape within the size range of 50-90 nm. The highest absorbance of alanine was of 74.8% at 12 h time and that of MB was 85.5% in 30 min [33].
The *Mimosa pigra* leaves extracts are used to remove aniline, MB, CR, and hydrogen peroxide (H₂O₂). The characterization of NPs was done using UV-Vis spectroscopy, PXRD, and TEM. 17.5 nm for Ag and 49.5 nm for Ag associated with CuO were the average sizes obtained in the analysis. These plant extracts were used for capping as the O–H and C = O groups. The broadbands appeared in the range of 400–500 nm with some diffractions in the spectrum of Ag-CuO NP. The crystallite size of Ag-CuO at about 50 nm was determined from the XRD results using Scherrer’s equation [34].

The *A. elagaignoides* flower extracts were used for synthesizing CuNPs, and high levels of phenolic compounds were observed in it, whereas other phytochemicals acted as capping as well as reducing agents. FT-IR band at 450 cm⁻¹ which were recognized because of the vibrations of Cu-O gave a confirmation of the NPs formation in addition to proteins and phenolic compounds. XDR analysis showed the crystalline structure with FCC structure. TEM results exhibited the NPs size between 36 and 54 nm, and the NPs showed a high catalytic activity in the aqueous phase for the reducing of MB, CR, and 4-nitrophenol (4-NP) only in presence of NaBH₄ at room temperature. Also, by using centrifugation, we can easily recover NPs catalyst and reuse it for up to 6 cycles with still showing a maximum of 90% conversion efficiency [35].

In another study, the research was focused on the green synthesis of magnetite (Fe₃O₄-gNP)s NPs using the coprecipitation method from *Moringa oleifera* and its efficiency for removal of antibiotic; levofloxacin from various aqueous solutions was studied. The average size of the NPs was 14.34 nm and was further evaluated for its adsorption capacity and removal of contaminant. The adsorption batch experiments (adsorbent (NPs) dosage, initial concentration of adsorbate, pH, contact time, and temperature) were conducted to determine the reaction mechanism by studying kinetics while fitting isotherm models. The results exhibited that the maximum adsorption capacity was achieved at equilibrium 22.47 mg/g and that 86.15% removal efficiency of 4 mg/l levofloxacin was achieved by 100 mg/l NPs in 24 h contact time. The experiments were conducted in four cycles for reusability and removal efficiency varied from 85.35% to 80.47%, indicating a very high potential of reusability of the adsorbents [36].

The NPs synthesis using plants is an environmentally friendly and inexpensive biological synthesis method. In this study, Ag-NPs were synthesized via *Aloe barbadensis* through biological process which is very environmentally friendly. The FTIR, spectroscopy analysis, and UV-Vis spectrophotometer are used for characterization. The research is based on using silver and copper NPs for wastewater purification. Water contaminated with naphthalene is used in and is further decontaminated and purified using nanoparticles. Similarly, many such other organic compounds are removed with plant-based NPs which are cost efficient, easy, quick, and effective [37].

### 2.3. Role of Phytonanotechnology for Removal of Dyes

Dye effluents from textile industries have contributed to the worldwide concern of environmental pollution. Various industries exploit over 10,000 distinct forms of dyes and pigments. Diverse forms of artificial dyes are found in wastewaters owing to the poor uptake of those dyes through fabrics. The nature of wastewater can be deciphered when parameters such as oxygen demand (BOD and COD), pH, salinity, temperature, robust color, nonbiodegradable natural compounds, and total dissolved solids present are considered. An integral part of wastewater remediation is green synthesis of NPs and subsequent removal of dyes. Methylene blue, Congo red, malachite green, and methyl green are among the many kinds of dyes retrieved from wastewater resources. NPs of silver, iron, copper oxide, and zinc oxide obtained were analyzed for particle size, and the degradation efficiencies were also calculated [38].

To synthesize NPs using biogenic synthesis, the leaf extracts of *Syzygium cumini* (Jaman) were employed for the degradation of methylene blue. Preceding alcoholic synthesis, the fabrication of ZnO NPs using the leaf extract was calcinated at 500°C for 4 h. The heating was performed at 80°C in the presence of zinc acetate followed by cooling, continuous heating, and filtration. As confirmed by XRD analysis, the ZnO NPs exhibited hexagonal packing and average crystallite size of 11.35 nm. Furthermore, the increase in the pH value resulted in an enhanced degradation (74.3 ± 4.2%, 87.4 ± 2.9%, and 89.96 ± 1.8% at the pH values of 6, 10.4, and 12.6, respectively) of the dye [39].

In addition to phase formation, functionality, and chemical composition, morphological features and surface area of the biohydrothermally synthesized ZnO-ZnFe₂O₄ NPs impregnated onto leaf extract of *Psidium guajava*. The prepared NPs (17.8 nm) effectively mediated the water remediation process as well as enhanced the immunity of the plant. At a constant adsorbent dose and contact times between 30 and 180 min, the batch adsorption method served as the ideal means of preparation for the given NPs. When estimated using the pseudo-second order kinetics and Langmuir isotherm models, the maximum adsorption rates were 120.32 mg/g for CR and 90.35 mg/g for MB. Due to high surface-active sites, the dye removal efficiency of CR and MB is at 96% and 90%, respectively [40].

The leaf extract of neem (*Azadirachta indica*) was impregnated with freshly synthesized copper oxide NPs (CuO-NPs) at room temperature. The NPs with an average size of 21.6 nm, synthesized biogenically, degraded 94.5% of total methylene blue dye in 20 min at a higher dose of NPs in 20 ml of 10 ppm dye, under different reaction conditions (time of contact, exposure to UV light, dose, temperature) of the reaction mixture. The recorded dye removal percentage changed from 93.8 to 94.5% at a higher dosage (480 μl) of NPs in 20 ml of 10 ppm [41].

Magnetic ferric oxide NPs (FONPs) were fabricated using the leaf extract of *Peltophorum pterocarpum*. The NPs were 16.99 nm in size and exhibited rod-like and crystalline morphology, showing agglomerations with γ and α-Fe₂O₃ phases after FE-SEM analysis and XRD imaging. With a pore diameter of 7.92 nm, the large FO-NPs were characterized as mesoporous and possessed a surface area of 66.4 m²/g as per BET analysis. For the MB dye degradation,
the Fenton-like catalytic efficiency of the FO-NPs was estimated at 90% removal within 220 min. A suitable second order model demonstrated the experimental results with a degradation constant of 0.09871/mg min. 92% dye degradation within 27 min was obtained when NaBH₄ was used as a reducing agent for the evaluation of catalytic potential of the FO-NPs with a first-order model demonstrating the results optimally at a kinetic degradation constant of 0.085/min [42].

Gold NPs (ANL-AuNPs) of size 21.52 nm were impregnated onto plant extracts of *A. nigra* and were characterized by the UV-Vis spectroscopy, FTIR spectroscopy, XRD, and TEM imaging. In the presence of sunlight, ANL-AuNPs catalyzed the degradation of the pollutant dyes, methyl orange, and rhodamine B with percent degradations of 83.25% and 87.64%, respectively. Polyphenolics and other key functional groups present in the aqueous extract played the role of reducing and capping the metal ions in the Au-NPs and were identified using FTIR spectral analysis. Furthermore, this green synthesized NP also exhibited the capacity of inhibiting the growth of some bacteria and antioxidant activity. *Candida albicans*, a pathogenic fungus, were susceptible to this property [43].

The photocatalytic degradation of methyl orange and rhodamine B as anthropogenic pollutant dyes was performed with percent removal of 83.25% and 87.64%, respectively, under a pseudo-first-order kinetic model. The green iron NPs (INPs) were prepared using the *Chlorophytum comosum* aqueous leaf extract. The water dispersion of the leaf extract served as a suitable reducing and capping agent for the spherical, amorphous NPs below 100 nm in size corresponding to their TEM images. Within a span of 6 h, 77% of total methyl orange concentration was eliminated by the synthesized I-NPs. The UV-Vis spectroscopy can reveal the concentration of methyl orange dye by the I-NPs in the presence of H₂O₂. The Antibacterial activity against both Gram-negative and Gram-positive bacteria was suggested by the NPs in addition to dye degradation [44].

Determination of the stability, as well as reusability of the various nanoparticles, was also achieved. The zinc oxide NPs were synthesized in another study in the presence of jujube fruit *Ziziphus jujuba* extract as a reducing agent and a stabilizer. The stable photocatalytic activity was demonstrated by the NPs after sequential degradation experiments. The stability and reusability were determined by stable performance of the NPs up to 4 cycles [45].

The highly efficient and stable photocatalysts were obtained as biogenically synthesized AgNPs using the seaweed extract of *Ulva lactuca*. The Ag-NPs were synthesized biometrically within 48 h of incubation time. The average size of the particles was confirmed to be around 48.59 nm and of spherical shape by HR-SEM. The NPs were suggested to be highly stable in colloidal solution due to a negative zeta potential value of −34 mV. At different time intervals, the photocatalytic degradation of the methyl orange dye was investigated using silver nanocatalysts by solar irradiation techniques. Degradation of the dye was visualized by decrease in peak intensity within 12 hours of incubation time [46].

Using plant extract of *Fraxinus chinensis* Roxb. in the presence of the coexisting ions (Pd, Cd), the phyrogenic magnetic NPs (PMNPs) were synthesized and functionalized; hence, the material can exhibit high selectivity and faster separation times (35 s). These NPs are suitable for eliminating toxic organic compounds and dyes with visible light illumination under ambient temperature. 3-mercaptopropionic acid (3-MPA) demonstrated an adsorptive capacity of 81.2 mg/g at 25°C and the highest adsorptive rate (98.57% MG removal within 120 min) persisting over a wide pH range (6–12). A removal efficiency of more than 85% was further obtained when the adsorbent (3-MPA@PMNPs) was recovered and reused for a total of five times [47].

Iron oxide and iron NPs are extremely effective NPs for industrial level production. The capping and reducing capacity displayed by the aqueous extract of *Daphne mezereum* was exploited to obtain stable iron oxide NPs (IONPs) ranging from 6.5 to 14.9 nm. The extract prepared after centrifugation resulted in a clear solution that was refrigerated. A mean particle size of 9.2 nm was obtained after preliminary characterization using TEM, particle size analysis (PSA), FTIR spectroscopy, XRD, vibrating sample magnetometer (VSM), and thermogravimetric analysis (TGA). The photocatalytic efficiency of the INPs on methyl orange was investigated and determined at 81% within 6 h using UV-Vis spectroscopy [48].

The iron-silver core-shell nanoparticles, iron-gold core-shell NPs, and iron NPs were synthesized using the pomegranate peel extract (PEP) for the removal of stock solutions of aniline dye from water resources prepared by dissolution of the dye in double distilled water. The FeO/AgNPs less than 100 nm in size showcased iron cores 13 nm in size, while the shell of the NPs was 14 nm in size. Degradation efficiency of the NPs was maximized by optimizing the reaction parameters such as NP and dye concentration, pH, temperature, and contact time, i.e., 30, 60, 90, 120, and 150 min. Substantially higher in alkaline range, the acidic pH proved to be unfavorable for dye removal. 95% and 90% dye degradation efficiency were noted for FeO/Ag-NPs and FeO-NPs at 0.5 mg/ml and 0.25 mg/ml, respectively [49].

High antioxidant content of the peel extract of *Artocarpus heterophyllus* has been reported, and coupled with its bioreducing, capping, and stabilizing potential, it serves as a potential source of valuable biomolecules for the green synthesis of iron NPs (FeNPs) with an average size of 33 nm. Iron oxides and oxyhydroxide form the majority of zero-valent iron NPs (nZVI) and thus obtained. The pseudo-first-order model was used to understand the reaction mechanism at 44.85 °C, demonstrating a Fenton-like 87.5% catalytic degradation of pollutant dyes like Fuchsin Basic by the NPs in 20 min [50].

The toxic pollutants such as rhodamine B, BV10 (basic violet 10), BB9 (basic blue 9), AR51 (acid red 51), and BPB (bromophenol Blue) were effectively degraded using green synthesis. The biosynthesized hexagonal wurtzite crystalline zinc oxide NPs (ZnONPs) with nanoflower morphology, zinc, and oxygen bonding vibrations at 557 cm⁻¹, 511 cm⁻¹, and 433 cm⁻¹ (FTIR) and an average size of 13.33 nm were characterized by the UV-Vis spectroscopy, SEM, EDS, XRD, BET, and other techniques to contain phytocomponents retrieved from the zinc acetate precursor and leaf
extract of *Cyanometra ramiflora* that can aid in the reduction of zinc ions. At 360 nm in the UV-Vis curve, a sharp absorption maximum was observed, indicating that the formation of ZnO NPs strong signals were exhibited by EDS for zinc and oxygen elements. 98% photocatalytic removal within 200 min of contact under sunlight irradiation against rhodamine B with a degradation constant of 0.017 min⁻¹ suggested a remarkable degradation efficiency [51].

The dried flowers of *Convulvulus fruticosus* were macerated, filtered, and condensed to obtain a pure solid flower extract for the synthesis of gold NPs with an average particle size of 35 nm after the FE-SEM, TEM, and DLS analysis. The degradation of the dyes were accounted for 94.3%, 90.2%, and 85.4% under UV and 80.6%, 79.8%, and 73.3% under visible light irradiation for basic violet 10 (BV10), basic blue 9 (BB9), and acid red 51 (AR51), respectively, demonstrating the photocatalytic capacity of the NPs [52].

Filtered extract of the seed powder obtained from *Punica granatum* seed extract was used after centrifugation for the fabrication of irregular-shaped hematite nanoparticles. The synthesized α-Fe₂O₃ NPs exhibited an average size of 26.53 nm as indicated by the FE-SEM and TEM analysis. The BET analysis on the other hand revealed a stable yet sus-

2.4. Role of Phytonanotechnology for Removal of Pathogens. 
Global public health is now facing an alarming threat in the form of human pathogens. Resembling the intestines of an individual, the wastewater treatment plants (WWTPs) serve an important role of receiving and digesting various pathogens infringing on human lives. Phytonanotechnology is one such strategy that enables the removal of pathogens from WWTPs in an eco-friendly, affordable, and effective manner.

The biocidal properties of copper and copper-associated complexes coupled with their relative ease of availability in plant biomaterials, exceptional thermal, and electrical conductivity make them ideal bioabsorbers and antimicrobial agents. CuO NPs were incorporated into the plant extract of *Madhuca longifolia*, which is a nontoxic reducing agent and has high biocompatibility. XRD patterns revealed peaks at 2θ = 32.58°, 35.15°, 35.67°, 36.64°, 38.86°, 49.05°, 57.51°, and 58.46°, while FTIR spectra affirm crests for Cu–O bonding at 480, 540, 660, and 670 cm⁻¹. The UV-Vis spectroscopy studies revealed mixed phase Cu (OH)₂ and CuO NPs being formed in the process with peaks within the range of 240–390 nm. Furthermore, distinctive spikes around 380 and 480 nm values determine the formation of NPs as valid. TEM suggested that the NPs have a spherical structure with the size of 120 nm which were dispersed evenly, but at some points, aggregations of the same were also observed. Using the well diffusion method, the bacterial removal capacity of the composites was checked for *E. coli BL21 DE3*, *S. aureus*, and *B. subtilis*, which largely depends on the size of the nanoparticles, their concentration, and stability along with the concentration of the growth medium and the type of bacterial cultures tested against the nanoparticles. Zones of inhibition in the range of 15.67 ± 058 mm and 14.67 ± 058 mm suggest moderate removal efficiency against *S. aureus*, *B. subtilis*, and *E. coli BL21 DE3*. Lastly, photocatalytic removal of MB under visible light irradiation is affected by agglomeration and is capped at 77% and 46% for the two samples [54].

The innovation of a novel, green, economical, and reproducible chemical reduction method that employs shredded bagasse and rice husk subsuming copper NPs (for the potential treatment of potable water via the removal of *E. coli*) was carried out by Bashir et al. The inductively coupled plasma optical emission spectroscopy (ICP-OES) analysis captured an increment in copper concentration in modified rice husk and bagasse as up to 38.5 mg/g and 29.9 mg/g as compared to 2.7 mg/g and 3.6 mg/g in their respective raw forms. The SEM analysis highlighted the absence of any ligand or stabilizing agent as a supplement, which resulted in undulating surfaces on fiber bundles and aggregation of Cu-NPs. When used in the range of 0.5–3.0 g/100 ml of water at a pH between 5 and 9 and a contact time of 100–120 min, the antimicrobial removal efficiency increased nearly twofold from 46% to 95% for bagasse and 48% to 100% for rice husk incorporated with nanoparticles, lasting for a period of 5 weeks [55].

Silver and silver-related compounds are highly sought-after in commercial markets due to their desirable chemical stability, catalytic, and antimicrobial activity alongside copper. The *Phyllanthus pinnatus* stem extract was used for the biogenic fabrication of silver NPs (AgNPs) less than 100 nm in size (SEM). Alkaloids, saponins, alcohols, phenols, terpenes, and proteins accelerate the synthesis of these NPs and reduce Ag⁺ to Ag with minimal cost, less time, and absence of any toxic by-products. λmax absorption peak was obtained at 490 nm by SPR from the UV-Vis spectroscopy, while the peaks at 3316 cm⁻¹, 1603 cm⁻¹, and 1036 cm⁻¹ highlight the stretching of O–H, bending of C = C, and vibration of C–N from FTIR. C–H stretching at 2918 cm⁻¹ possibly indicates the presence of methylene groups within the proteins, while O–H stretching could be linked to the bioreduction of the AgNPs by hydroxyl groups. The morphology of the NPs was described as crystalline by XRD studies and cubical, triangular, or spherical in shape at different magnifications according to SEM images. The antimicrobial activity was assessed via Kirby-Bauer disc diffusion assay on *V. cholera*, *S. flexneri*, *P. aeruginosa*, *M. smegmatis*, *P. vulgaris*, and *B. subtilis*. The NPs exhibited dose-dependent inhibition with maxima at 1.8 mm (40 μl) for both *V. cholera* and *S. flexneri* and 1.5 mm at 10 μl for *V. cholera* suggesting its sensitivity to the nanocomposite [56].

The biosynthesis of AgNPs was optimized by the UV-Vis method and facilitated with corn cob extract obtained from *Zea mays* in another study. The corn cob (CC) extract is rich in phenols, glucosides, and anthocyanins that offer
the property of antioxidation, while high contents of hemicellulosic sugars are useful for the fabrication of CC-AgNPs as agents for reduction or capping. UV-Vis analysis confirmed metallic NP formation through SPR bands formed between 400 and 430 nm. FTIR spectra have elicited strong bands at 3285 cm\(^{-1}\) for hydroxyl groups which shifted to 3334 cm\(^{-1}\) upon reduction with Ag. Furthermore, aryl ketones containing C = O bonds stretch at 1626 cm\(^{-1}\), while ketones (1631.70 cm\(^{-1}\)) and aromatic groups at 1350 cm\(^{-1}\) and 1412 cm\(^{-1}\). The powder XRD patterns provoke characteristic peaks at 20 values of 38.2°, 43.2°, 63.8°, and 77.0°, and through Scherrer’s equation, the resulting average crystallite size is estimated to be 13.55 nm for CC-AgNPs, while TEM studies show that the NPs are sized between 2 and 28 nm with spherical morphology. The antibacterial assays were performed using the diffusion method in the range of 0.5–8.0 \(\mu\)g/ml. CC-AgNPs exhibited dose-dependent inhibition with remarkable results at 8.0 \(\mu\)g/ml against B. cereus and S. aureus but not so much for S. typhimurium. Auxiliary investigations into the potential of the nanocomposite to behave as photocatalysts for the degradation of o-, m-, and p-nitrophenols and dyes such as Eosin Y and rhodamine 6G were also conducted with promising findings [57].

Malini, Kumar, and Hariharan et al. demonstrated the synthesis of chitosan-encapsulated green synthesized silver NPs (AgNPs) utilizing leaf extract of Prosopis juliflora using a simple ionic gelation method. The UV-Vis spectroscopy indicated absorption maxima at a wavelength of 420 nm, and distinctive peaks at 440 nm due to surface plasmon resonance of the oscillating electron present in the conduction band signify their biosynthesis. SEM imaging supported the findings from the UV-Vis spectroscopy, showing and smooth-surfaced nanocapsules with spherical morphology with average dimension of a particle as 30 nm as per the Debye-Scherrer equation. FTIR spectra of the plant extract confirmed its dual role as a reducing and capping agent due to the identification of key functional groups such as phenols (3409.28 cm\(^{-1}\)), alcohols (2929.28 cm\(^{-1}\)), alkanes (1774.43 cm\(^{-1}\)), ketones (1631.70 cm\(^{-1}\)), and aromatic compounds (1047.79 cm\(^{-1}\)). Leads were also obtained on the possibility of interaction between the AgNPs and NH\(_2\) groups present in chitosan. Zone of inhibition measuring 22 mm was obtained during antibacterial assays of E. coli test cultures against a culture of streptomycin as the positive control. Additionally, their capacity of removing heavy metals via biosorption and 83% photocatalytic degradation of rose Bengal dye within 2 h of contact provides us with a promising agent for the removal of water contaminants [58].

Asparagus racemosus was used to prepare silver NPs via a greener, eco-beneficial, and facile route. XRD pattern analysis catalogued the FCC structure of metallic silver, as well as the average crystallite size of the NPs to be around 20 nm. FTIR spectra demonstrated the presence of phenols, carboxylic acids, and amide linkages commonly noted in proteins. The scanning electron microscopy-energy dispersive X-ray analysis (SEM-EDX) investigation certified the formation of silver NPs as well as the presence of minute, spherical NPs, while the larger ones were formed possibly due to aggregation of smaller NPs. TEM images estimated the average size of NPs between 17 and 25 nm with smaller NPs reaching just beneath 10 nm. The antibacterial activity of the nanocomposites was assayed using Agar well diffusion; the NPs were dissolved in DMSO, and the wells were loaded with 50 \(\mu\)l (100 \(\mu\)g/ml) of AgNPs and incubated with cell cultures for 24 h. The MIC value for P. fluorescense, Y. ruckeri, E. tarda, and E. coli stood at 25 \(\mu\)g/ml and 12.5 \(\mu\)g/ml for A. hydrophila, F. branchiophilum, K. pneumoniae, S. aureus, and B. subtilis. The inhibition zones formed by AgNPs were 17.0 ± 0.89 mm and 16.0 ± 0.0 mm for S. aureus and B. subtilis, respectively, followed by 15.66 ± 0.51 mm, 14.5 ± 0.54 mm, 14.5 ± 0.54 mm, 13.16 ± 0.75 mm, 13.16 ± 0.75 mm, 13.0 ± 0.89 mm, and 12.33 ± 0.51 mm for F. branchiophilum, A. hydrophila, K. pneumoniae, E. tarda, Y. ruckeri, P. fluorescense, and E. coli, respectively. The enhanced antimicrobial activity of the nanocomposites and protection against aggregation was attributed to the metabolites present in root [59].

A facile, eco-friendly, and nontoxic chemical method was used to synthesize silver NPs (AgNPs) and incorporated onto the leaf extract of Pergularia daemia. The biogenic synthesis of the composite can be confirmed by a preliminary examination with AgNO\(_3\), UV-Vis spectrophotometry, and checking for SPR band peaks at 420 nm. The face-centered cubic (FCC) structure of fabricated NPs was affirmed by XRD patterns which elicited diffraction peaks at 2\(\theta\) of 37.4°, 46.1°, 64.2°, 78.1°, and 85.2°. FTIR peaks at 3415.31 cm\(^{-1}\) and 1600.63 cm\(^{-1}\) indicate the presence of functional groups like carboxylic acids and aliphatic or aromatic amines, respectively, that assist in the formation of AgNPs. FE-SEM analysis revealed that the silver NPs are spherical, do not aggregate, and show a size distribution of 30–45 nm. The dose-dependent antibacterial activity was measured against E. coli using well diffusion where varying concentrations of AgNPs were chosen as 10, 30, 70, and 90 \(\mu\)l. Lower concentrations (10 and 30 \(\mu\)l) demonstrated moderate inhibition and inconspicuous zones of inhibition, while higher concentrations (70 and 90 \(\mu\)l) produced clear inhibition zones. AgNPs showed significant antibacterial activity against most Gram-negative bacterial pathogens which suggests that the NPs can be used as an excellent biocidal agent [60].

Paradigm altering microwave and ultrasonically modified methods were combined and used in addition to Citrus paradisi peel extracts to synthesize a multifunctional, 3-layered Ag-MgO/nanohydroxyapatite (Ag-MgOnHaP) nanomodel. The UV-Vis analysis alludes to the color variation from light yellow to dark brown as well as the achievement of absorption maximum at 440 nm, which affirms the fabrication of silver nanoparticles. Formation of two intense bands at 290 nm and 378 nm denote the coalition of MgO with AgNPs and a blue shift of AgNPs from 440 nm to 378 nm, respectively. SEM images disclosed irregular flake-like morphology but soon transitioned to highly fine discrete shapes upon exposure to ultrasound. An Ag-MgOnHaP composite when subjected to TEM and ultrasound exposure between 20 and 100 nm resulted in an average mean particle size of 16.44 nm. The antimicrobial
capacity of the nanocomposite for *E. coli* subsequently formed 13 mm wide zones of inhibition, and 10 mm for *K. pneumoniae*. The defluoridation capacity through adsorption for these composites is 90% at 0.3 g dosage, 2.146 mg/g at 298 K. The sorption process follows the second order kinetics at room temperature and fit in well with Freundlich isotherms [61].

In another report, Naghizadeh et al. implemented a green, rapid, feasible, and cost-effective method for the synthesis of silver NPs (AgNPs) using *Jujube* core extract. The nanocomposites were prepared using a simple biogenic chemical method based on physicochemical characteristic studies to the likes of surface plasmon resonance (SPR) where peaks were obtained at about 420 nm. HPLC assay using a UV-Vis spectrophotometric detector at 275 nm attributed the biological activity of the extract to the presence of epicatechin, gallic acid, caffeic acid, p-coumaric acid, ferulic acid, and rutin. The crystalline structure of the NPs was ascertained using XRD patterns with sharp peaks at 2θ = 38.09°, 44.3°, 64.52°, and 77.43°. Images from FESEM and TEM estimated the average particle size between 25 and 50 nm, and 34 nm using Scherrer’s equation. Furthermore, declining intensity in SPR bands confirmed their optimal interaction period at 30–45 min. MIC and MBC values (µg/ml) were the least for *E. coli* at 1.25 and 1.25, which comments on their enhanced sensitivity, while *K. pneumoniae* and *S. aureus* are comparatively more durable against the nanocomposites with MIC and MBC values of 2.5 and 2.5 and 10, respectively. These zones of inhibition for *K. pneumoniae* and *S. aureus* are comparatively more durable against the nanocomposites with MIC and MBC values of 2.5 and 2.5 and 10, respectively. These findings were supported by the large surface area-to-volume ratio of AgNPs which helps in establishing contact. Lastly, anticancer and photocatalytic activities of the NPs against AGS cell line with an IC50 value of 249.9 µg/ml; with bactericidal rates of 99.96% to 99.99% and 94.29% for *S. aureus* [64].

The nanocomposites expressed good antibacterial activity against *S. aureus* from water. TEM images suggest that the NPs are relatively small and spherical (between 10 and 20 nm) and aggregate in large clusters within the organic material earlier present in the reductant. XRD patterns certify 12 nm as the smallest average crystalline size which can increase for higher annealing temperatures. The presence of phenols, alcohols, alkanes, ketones, and aromatic compounds was confirmed in FTIR in the wavenumber range of 3409.28 cm⁻¹, 2929.28 cm⁻¹, 1774.43 cm⁻¹, 1631.70 cm⁻¹, and 1047.79 cm⁻¹. The FTIR spectra also elicit bands of alkene and carboxyl groups on the surface of the NPs. The antimicrobial property of orange-peel extract is maintained by aromatic and saturated organic molecules such as tannins, saponins, phenolic compounds, flavonoids, and essential oils as reactive oxygen species (ROS). Thus, ZnONPs showed exceptional performance in inhibiting the growth of *E. coli* at 0.025 mg/ml after 8 h of incubation, with bactercidal rates of 99.96% to 99.99% and 94.29% for *S. aureus* [64].

ZnFe₂O₄/reduced graphene oxide nanohybrids (G-ZnFe₂O₄/rGO NHs) with high specific surface area, favorable electron transportation, good thermal and electrical conductivity, and biocompatibility that serve as an effective measure to control bacterial growth were synthesized using a natural surface-active peel extract. XRD patterns highlighted the successful formation of ZnFe₂O₄ with rGO as the G-rGO phase can be seen at 2θ = 26.35°. The results from FTIR proved the presence of different essential oxygen-containing functional groups such as carboxyls, hydroxyls, and ethers at 1632 cm⁻¹, 1401 cm⁻¹, and 1198 cm⁻¹, respectively. HR-TEM and SEM imaging allow us to observe the regular, smooth surface morphology of the NPs on rGO sheets with an average size of 30 nm. Photobacterial experimentation on G-ZnFe₂O₄ and G-ZnFe₂O₄/rGO NHs demonstrated significant results as the bacterial removal was reduced to 70.37 ± 4.2% upon being exposed to visible light for 40 min due to the synergistic action of ROS generation. Similarly, the nanohybrids also displayed tremendous cytotoxic activity against A549 cell line with an IC50 value of 249.9 µg/ml and, thus, can be used to removal organic dyes or pathogens from water [65].

*Zingiber officinale* (ginger) extracts were explored as an antimicrobial agent in conjunction with iron NPs (FeNPs) using a green, eco-friendly, facile, and benign approach as it offers anticancer, anticlotting, anti-diabetic, anti-inflammatory, and antioxidant effects. UV-Vis spectroscopy elicited characteristic peaks at 406 nm, while FTIR spectra when recorded between 500 cm⁻¹ and 4000 cm⁻¹ corresponded with the stretching of OH, C–H, and Fe–O bonds. XRD analysis implied that the synthesized NPs were 5.10 nm in size with 2θ = 32.43° and exhibited magnetite phase. SEM imaging showed stable nanocube-like crystalline structures. The nanocomposites expressed good antibacterial activity at 80 µl and 100 µl concentrations with zones of inhibition of *E. coli* at 20 and 22 mm when incubated for 24 h, respectively, as compared to the extract independently. Thus, this approach can be considered as a reliable and conclusive method for treatment of pathogens from water [66].

Pod extract from *Peltophorum pterocarpum* contains polyphenolic compounds, non-protein amino acids, polysaccharides, bergenin, and other metabolites that supplement the
| No. | Biomaterial | Name of biomaterial | Nanoparticles | Size of NPs | Contaminant removal | Capacity of removal | Time taken | Miscellaneous | Ref. |
|-----|-------------|---------------------|---------------|-------------|--------------------|--------------------|------------|---------------|------|
| 1.  | Leaf extract | *Ziziphus jujuba*  | ZnO           | 20 nm       | Pb(II)             | 80.68%             | 30 min     | The maximum removal of the Pb(II) was obtained by the application of the MWG ZnO NPs, compared with the G ZnO NPs, MWT ZnO NPs, and T ZnO NPs | [18] |
| 2.  | Leaf extract | *Syzygium Cumini*  | ZnO           | 10-12.55 nm | Methylene blue dye | 91.4%             | 180 min    | Photocatalytic degradation activity | [41] |
| 3.  | Fruit extract | *Ziziphus jujuba* | ZnO           | 20-37 nm    | Methylene blue (MB) | Degradation efficiency 85% | 5 h       | Has potential for the treatment of industrial wastewater from textile and rubber industries | [45] |
| 4.  | Leaf extract | *Cyanometra ramiiflora* | ZnFe₂O₄     | 13.33 nm    | Escherichia coli  | 98%                | 3 h 20 min | Antimicrobial activity, used in medicine, textiles, and cosmetics | [51] |
| 5.  | Leaf extract | *Sida rhombifolia* | ZnO           | 3.42 nm     | E. coli, Klebsiella pneumoniseae, Pseudomonas aeruginosa, Streptococcus mutans, and Staphylococcus aureus | 24 h | Antibacterial studies indicated that the NPs have the ability to destroy both Gram-positive and Gram-negative bacteria | [63] |
| 6.  | Peel extract | Orange              | ZnFe₂O₄      | 30 nm       | *Escherichia coli* | 70.57% ± 4.2%     | 40 min     | Due to the synergistic action of ROS generation, the nanoparticles exhibited excellent antibacterial properties | [65] |
| 7.  | Plant extract | *M. burkeana*       | ZnO–ZnFe₂O₄  | 25.03 nm    | Methylene blue and sulfoxazole | 99.8%             | 45 min     | Zinc ferrite nanoparticles Photocatalytic effect and degradation | [30] |
| 8.  | Leaf extract | *Psidium guajava*   | ZnO–ZnFe₂O₄  | 17.8 nm     | Congo red and methylene blue | 96% of CR and 90% MB | 150 min | The fabricated ZnO–ZnFe2O4 NPs enhance the plant immune response and promote plant growth, potentially by preventing transpirational water loss | [40] |
| 9.  | Bagasse and rice husk | Sugar and rice plant | CuNPs        | *E. coli*    | Up to 100%       | Bioabsorbent for decontamination of PAH | [55] |
| 10. | Leaf extract | *Azadirachta indica* | CuNPs        | Naphthalene | 98.07%            | 0-30 min     | Bacterial removal efficiency of CuNPs incorporated rice husk was measured 100%, higher than 95% achieved by using CuNPs incorporated bagasse | [69] |
| 11. | Leaf extract | *Tilia leaves*      | CuNPs        | Ibuprofen (Ibu), naproxen (Nap), and diclofenac (Dic) | Ibuprofen: 74.4% Nap: 86.9% Dic: 91.4% | 60 min | Follows the second order kinetic model for sorption; adsorption process was spontaneous and endothermic | [32] |
| 12. | Plant extract | *Madhuca longifolia* | CuO           | 30-120 nm   | *E. coli* BL21 DE3 Gram-negative, *S. aureus* Gram-positive, and *B. subtilis* Gram-positive | 24 h | Selectively effective against various strains of microorganisms | [54] |
| No. | Biomaterial   | Name of biomaterial | Nanoparticles | Size of NPs | Contaminant removal                  | Capacity of removal | Time taken | Miscellaneous                                                                 | Ref.       |
|-----|---------------|---------------------|---------------|------------|--------------------------------------|---------------------|------------|--------------------------------------------------------------------------------|-----------|
| 13. | Leaf extract  | Azadirachta indica  | 21.6 nm       | Methylene blue | 93.4–93.75% (lower dose) 93.8–94.5% (higher dose) | 0-20 min           |            | The leaves extract contains phytochemicals which act as reducing, capping and reducing agents | [41]       |
| 14. | Flower extract| Aglaia elaeagnoides | Copper nitrate | 20–45 nm   | 4-Nitrophenol                        | 90%                 |            | Catalytic activity on pernicious dyes such as Congo red and methylene blue; NPs can be recovered and reused for 6 cycles by centrifugation | [35]       |
| 15. | Stem extract  | Phyllanthus pinnatus | >100 nm       | V. cholera, S. flexneri, P. aeruginosa, M. smegmatis, P. vulgaris, B. subtilis Escherichia coli, Staphylococcus aureus, Bacillus subtilis, Klebsiella pneumonia, Pseudomonas fluorescens, Aeromonas hydrophila, Edwardsiella tarda, Flavobacterium branchiphilum, and Yersinia rukeri | 24 h               |            | Zones of inhibition formed shows efficient antibacterial activity               | [56]       |
| 16. | Root extract  | Asparagus racemosus  | 10-17 nm      | AgNPs      |                                      | 24 h               |            | Economical eco-friendly and green synthetic material                          | [59]       |
| 17. | Leaf extract  | Prosopis juliflora  | 30 nm         | Escherichia coli, Rose Bengal dye, heavy metal | 83% - rose Bengal dye 81% - heavy metals 24 h, 0-30 min, 45-180 min, respectively | 24 h               |            | Nanoparticles synthesized can be used for wastewater treatment                | [58]       |
| 18. | Leaf extract  | Pergularia daemia    | 30-45 nm      | Escherichia coli | 24 h                              |                     |            | AgNPs can be used as a good biocidal agent against bacterial pathogens       | [60]       |
| 19. | Leaf extract  | Aloe barbadensis     | AgNP s         | Naphthalene decontamination | 90%                                           |                     |            | Three different plants precursors are used for the synthesis of plant extracts such as Aloe barbadensis, Azadirachta indica, and Coriandrum sativum that are further used to synthesize nanoparticles. Two different nanoparticles are obtained such as silver nanoparticles (Ag-NPs) and copper nanoparticles (Cu-NPs) ANN modeling was used as it does not require mathematical description of the phenomena involved in reduction process | [69]       |
| 20. | Kernel extract| Terminalia bellirica | 32 nm         | 4-Nitrophenol | 87%                                            |                     |            | Displayed excellent photocatalytic properties                                | [29]       |
| 21. | Leaf extract  | Mimosa pigra        | 17.5 nm       | Methylene blue, hydrogen peroxide | 55-60% MB 22-45% H2O2 | 48 h             |            | Excellent antioxidant and antimicrobial action against E. coli, F. oxysporum, and V. dahliae | [34]       |
| 22. | Peel extract  | Citrus maxima       | 4 – 11 nm     | 4-Nitrophenol   | ~100%                                        |                     |            |                                                                                  | [27]       |
| No. | Biomaterial | Name of biomaterial | Nanoparticles | Size of NPs | Contaminant removal | Capacity of removal | Time taken | Miscellaneous |
|-----|-------------|---------------------|---------------|-------------|---------------------|--------------------|------------|---------------|
| 23  | Husk extract | *Juglans*           | Petroleum wastewater (Pb, Cr, Cd) | 46.2 nm | Pb 72.6%<br>Cr 81.3%<br>Cd 88.1% | 5 h | New nanoscale bio-based nanocomposite | [13] |
| 24  | Leaf extract | *Pliostigma thonningii* | Cu++          | 70-114 nm | 82.1%                | 1 h | Treatment of diseases such as ulcers, diarrhea, dysentery, worms, and other intestinal problems | [19] |
| 25  | Leaf extract | *Ficus benjamina*  | Cd++          | 60-105 nm | 75.5% (100 mg/L)<br>85% (50 mg/L) | 40 min | In a source of indoor allergens, symptoms include allergic asthma and rhino-conjunctivitis | [14] |
| 26  | Seed extract | *Moringa oleifera* | Pb++          | 9.4 nm | >80%                  | 30 min | Photocatalysis of organic dyes and compounds and antimicrobial activity | [70] |
| 27  | Peel extract | *Citrus paradisi* | Ag-MgO (Klebsiella pneumonia and Escherichia coli) | 16.44 nm | Methylene blue, methyl orange, 4-NP, 2A-DNPH | 24 h | Effective in the reduction of pollutants using NaBH4 in water | [28] |
| 28  | Plant extract | *Acalypha hispida* | FeNPs-JCE (E. coli and K. pneumoniae as Gram-negative bacteria and S. aureus as Gram-positive bacteria) | 23 nm | Methyl orange dye | 60 s | FESEM, TEM, XRD, FT-IR, EDS, and UV–Visible spectroscopy | [62] |
| 29  | Fruit extract | *Jujube*           | AgNPs-JCE     | 25–35 nm | Fe2O3 (Methyl orange dye) | 81% | Zingiber officinalis root has important role in pharmaceutical industry | [66] |
| 30  | Ginger extract | *Z. officinale* | Fe3O4          | 5.10 nm | Levofoxacin | 89.42% for CR and 87.96% for BPB dye | 24 h | (Iron nanoparticles) INPs are also employed as a Fenton-like reagent | [44] |
| 31  | Leaf extract | *Chlorophyllum comosum* | FeNPs | <100 nm | Methyl orange dye | 77% | FeNPs | [44] |
| 32  | Peel extract | *Artocarpus heterophyllus p* | α-Fe2O3 (Methylene blue dye) | 33 nm | Methylene blue dye | 81% | 6 h | The peel has high antioxidant content which is a valuable biomolecules and act as the bioreductants | [50] |
| 33  | Leaf extract | *Daphane merezeum* | Fe2O3          | 9.2 nm | Methyl orange dye | 90% | 3 h 40 min | In an ornamental tree, its foliage is used as a fodder crop | [42] |
| 34  | Leaf extract | *Petrophorum pterocarpum* | Fe3O4          | 16.99 nm | Methylene blue dye | 89.42% | 240 min | The magnetic properties of the material are directly related to their recovery and reuse in practical applications | [53] |
| 35  | Seed extract | *Punica granatum* | Fe3O4          | 5.54 nm | Congo red (CR) and bromphenol blue (BPB) | 89.42% | The potential pathway for the removal was by chemisorption | [37] |
| 36  | Leaf extract | *Moringa oleifera* | Fe3O4          | 14.34 nm | Levofoxacin | 86.15% | 24 h | [37] |
| No. | Biomaterial | Name of biomaterial | Nanoparticles | Size of NPs | Contaminant removal | Capacity of removal | Time taken | Miscellaneous | Ref. |
|-----|-------------|---------------------|---------------|-------------|---------------------|--------------------|------------|---------------|------|
| 37  | Peel extract | *Punica granatum* | FeO/Ag         | 27 nm       | Aniline blue (AB) dye | 11-90%             | 30-150 min | Suitable for application in water purification techniques | [49] |
| 38  | Leaf extract | *Simarouba glauca* | GT-nFe         | 9 nm        | Lead (II)           | 80%                | 5-60 min   | The obtained NPs were reused for up to 3 times | [10] |
| 39  | Leaf extract | Green tea          | Cr(VI)         | 99.9        | Cr(VI)              | 100%               | 5 min      | Experiments were performed in a batch photoreceptor | [8] |
| 40  | Leaf extract | Barberry plant     | GnZVI          | 20-40 nm    | Cr(VI)              | 96%                | 30 min     | By using the effect of gamma radiation | [17] |
| 41  | Black tea (BT) | Powder extract | ZVI NPs | 6.1 to 10.6 nm | Cu2+ | 82% | 50 min | Decolorization of toxic textile dyes like methylene blue | [33] |
| 42  | Flower extract | *Calotropis gigantea* | F-Fe0: 2.46 nm to 11.49 nm | Aniline | 49.4% | 12 h | Iron nanoparticles (F-Fe0) and Ag with different absorbants have different efficiencies and time requirement | [24] |
| 43  | Leaf extracts | *Ipomoea carnea* | Ag and F-Fe0 | 2.46 nm to 11.49 nm | Chlorfenapyr | Variable | 1-2 weeks | The synthesized NPs were of varied shapes | [23] |
| 44  | Fruit extract | Lemon              | ZVI NPs | 30 nm       | Pb                  | 100%               |            | The residual concentrations of TCs were determined using an Agilent Technologies 1260 Infinity II HPLC system equipped with a UV detector | [23] |
| 45  | Flower extract | *Convulvulus fruticosus* | AuNPs | 35 nm       | Basic violet 10 (BV10) Basic blue 9 (BB9) Acid red 51 (AR51) | 73.3%-94.3% | 15-60 min | Essential for biological and removal of toxic pollutants for water purification | [52] |
| 46  | Leaf extract | *Alpinia nigra*   | 21.52 nm      | Methyl orange dye | 83.25% | 2 h | Antioxidant and antimicrobial activity | [43] |
| 47  | Seed extract | *Lawsonia inermis* | Au-Ag         | 15-35 nm    | 4-Nitrophenol       | 100%               | 3-20 min   | A simpler and greener method for the synthesis of Au-Ag NPs using the aqueous fraction of L. inermis seed extract with ultrasonification | [31] |
| 48  | Leaf extract | Eucalyptus         | Triclosan (TCS) and copper (Cu(II)) | 9 min | | | | | The residual concentrations of TCs were determined using an Agilent Technologies 1260 Infinity II HPLC system equipped with a UV detector | [23] |
| 49  | Straw waste |                       | Cr(VI)       | 58.1% to 99.7% | Cr(VI) | 58.1% to 99.7% | 4 h | | [11] |
| 50  | Leaf extract | Green tea          | rGO-Fe/Ni     | 20–80 nm    | Sb(III)            | 95.7%               | 3 h        | Bimetallic iron/nickel nanoparticles were loaded with graphene oxide forming rGO-Fe/Ni | [15] |
| No. | Biomaterial         | Name of biomaterial       | Nanoparticles   | Size of NPs | Contaminant removal                  | Capacity of removal | Time taken | Miscellaneous                                                                 | Ref.     |
|-----|---------------------|---------------------------|-----------------|-------------|--------------------------------------|---------------------|------------|---------------------------------------------------------------------------------|----------|
| 51. | Rice residue        | ZBC                       | As(III) and As(V) | —           | Variable                             | Zirconium (hydro) oxide (Zr(OH)₄ or ZrO₂) particles have been documented as a potential adsorbent agent for the removal of As(III) and As(V) from waters | [16]     |
| 52. | Peel extract        | *Pomegranate*             | TiO₂            | 92.8 nm     | *Staphylococcus aureus*, *Escherichia coli*, *Pseudomonas aeruginosa* | 99.9%               | 24 h       | PPP-TiO₂ was confirmed to have antibacterial susceptibility properties against Gram-positive and Gram-negative bacteria | [68]     |
| 53. | Plant extract       | *Konjac glucomannan*      | Pd NPs          | 6.48 ± 2.19 nm | Cr(VI)                               | —                   | —          | Calculated absorbance were 93.4% by 120 min, 89.1% by 90 min, 83.2% by 135 min, 79.3% by 150 min, 77.1% by 120 min, and 70.1% by 250 min for MO, AR I, PC, AV7, GO II, and AO74 degradation, respectively | [9]      |
| 54. | Leaf extract        | *Fraxinus chinensis Roxb.*| Phytoogenic magnetic nanoparticles (PMNPs) | Malachite green (MG) | 98.57%                              | The equilibrium adsorption time was different for the different concentrations of MG dye | [47]      |
formation of magnetite (Fe₃O₄) NPs. Visual studies show that the solution changes color from colorless to greenish black. UV-Vis experiments do not yield a distinct peak but more so a continuous absorption band spanning from 300 nm to 800 nm. SEM analysis confirmed the spherical morphology of NPs with little to no aggregation. EDS was crucial in uncovering the primary elements present in the composite (Fe and O). Powder XRD pattern of PP-Fe₃O₄ NPs revealed several sharp peaks which helped in determining the crystallite size of the NPs as 23.82 nm. Bactericidal action of the PP-Fe₃O₄ NPs is enhanced because of their high surface area-to-volume ratio. Using agar well-diffusion assay on _E. coli_ and _S. epidermidis_, the zones of inhibition were noted at 15 and 12 mm, respectively, for 60% concentration, 18 and 13 mm, respectively, for 80% concentration, and 19 and 15 mm, respectively, for 90% concentration, and 20 and 16 mm, respectively, for 100% concentration when incubated for 24 h with PP-Fe₃O₄ NPs. Lower values of inhibition zone for _E. coli_ stems from its thick peptidoglycan layer which can resist the penetration of the PP-Fe₃O₄ NPs. Similarly, the photocatalytic potential of the PP-Fe₃O₄ NPs was calculated to be 88.98% for MB dye 45 min after exposure [67].

Pristine pomegranate peel extract (PPP) was impregnated with TiO₂ NPs to fabricate metal matrix nanocomposites (MMC) capable of inhibiting microbial growth for the treatment of water resources. Characterization of the NPs began with SEM imaging where the images of PPP before and after loading with TiO₂ NPs were visualized. Arbitrarily oriented and irregular grains with sharp boundaries, micro-cracks, and aggregates could be seen. On the other hand, large grains with smooth surfaces, sharp boundaries, and no discernible eruptions were observed in PPP-TiO₂ NPs. Surface charge present on the NPs was evaluated using ζ-potential values. For TiO₂ NPs, ζ-potential is -6.95 mV and is -11.4 mV for PPP-TiO₂ NPs signifying a good distribution of particles. Powder XRD patterns estimate average crystallite size of TiO₂ NPs is 92.8 nm using Scherrer’s equation. The XRD pattern of PPP exhibited single broad peak signifying amorphous character, and thus, calculating the average crystallite size can be difficult. The broch microdilution method was used for the assay where MIC₉₀, MIC₅₀, and MBC for each of the three microorganisms were estimated. 99.99% of _S. aureus_ colonies were eliminated at 200 μg/ml, and the same removal efficiency for _E. coli_ and _P. aeruginosa_ could be achieved if the concentration of PPP-TiO₂ NPs exceeds 310 μg/ml and 315 μg/ml, respectively [68].

Details of the application of plant-source-mediated nanoparticles in the remediation of wastewater contaminants have been listed in Table 1.

### 3. Conclusion

The current review addresses the application of nanomaterials contrived from plant-based products as an affordable yet eco-friendly and reproducible strategy for the remediation of heavy metals, organic compounds, dyes, and pathogens from the environment. Their physicochemical properties were identified by drawing on standard laboratory techniques such as TEM, SEM, UV-Vis spectroscopy, XRD, FTIR, SAED, and EDX, among others. Through reduction and absorption mechanisms, the crystalline NPs either independently or in conjunction with other chemicals or reagents removed contaminants within the environment with a certain degree of efficiency depending on the resource used, mode of production, or external parameters such as temperature or pH. Despite their recyclability, rapid reaction time, and high elimination efficiency (~70%), their fragility and susceptibility to ineffectiveness outside of an environment with physically optimum conditions currently restrict any attempts at large-scale commercialization. Nevertheless, with continual advancements in technology and research, the development of feasible protocols for wastewater quality improvement may become plausible.

### Data Availability

All relevant data are included within the article.

### Conflicts of Interest

All authors declare that there is no conflict of interest.

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