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Original article

PHYTOSYNTHESIS OF SILVER NANOPARTICLES USING *Dryopteris filix-mas* (MALE FERN) AND ITS POTENTIAL APPLICATION IN THE REMEDIATION OF TEXTILE WASTEWATER

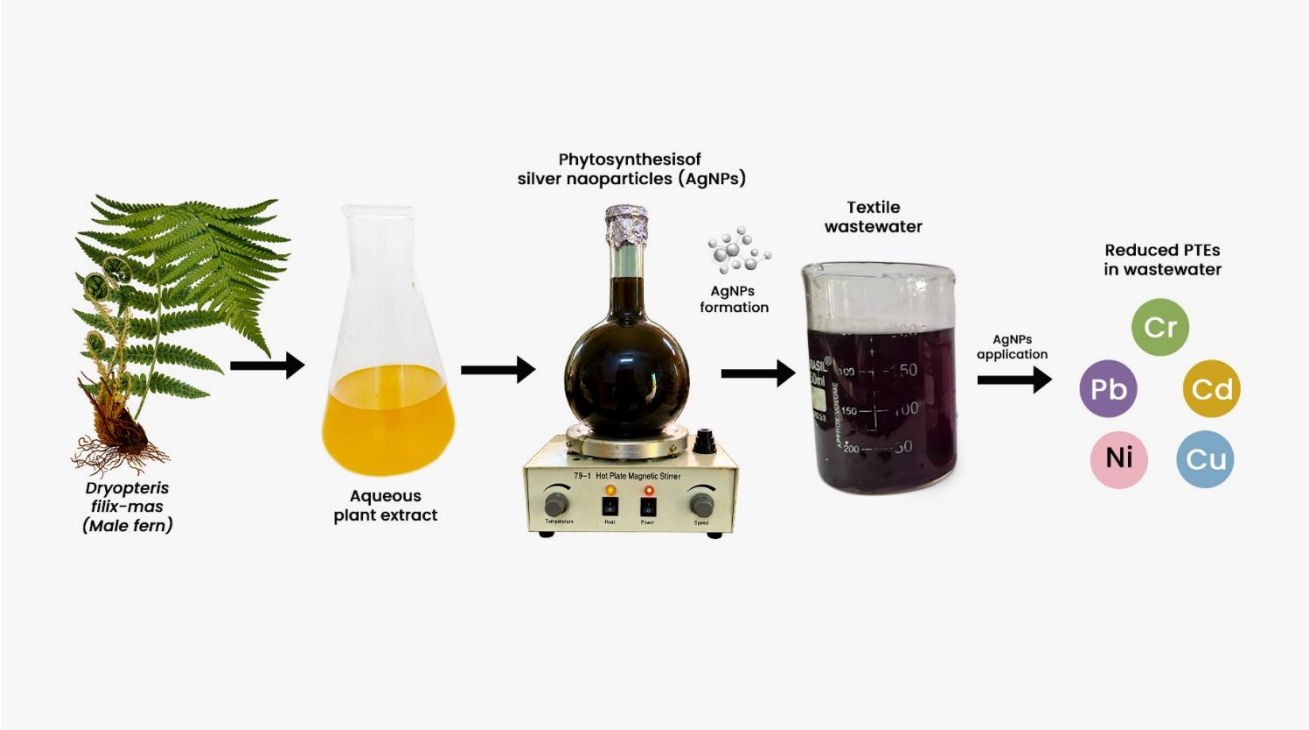
Olajide Keshinro[1], Olanrewaju Oloyede[2], Taobat Keshinro[3], Khadijat Oreshile[4], Simeon Asokere[5]
[1-5]Lagos State University, Ojo, Lagos State, Nigeria, Nigeria
Corresponding Author : olajide.keshinro@lasu.edu.ng

ABSTRACT

Textile industries discharge large volumes of wastewater containing potentially toxic elements (PTEs), which pose serious environmental and public health risks. This study reports the green synthesis of silver nanoparticles (AgNPs) using *Dryopteris filix-mas* (L.) Schott leaf extract and evaluated their potential for the remediation of textile wastewater collected from Idi-Aro, Abeokuta, Ogun State, Nigeria. The synthesised AgNPs were characterised using Fourier transform infrared spectroscopy, scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy, transmission electron microscopy (TEM), and X-ray diffraction (XRD), while the PTEs concentrations before and after treatment were quantified by an atomic absorbance spectrometer. The untreated wastewater contained 0.990 ± 0.089 mg/L chromium (Cr), 0.374 ± 0.144 mg/L lead (Pb), and 0.343 ± 0.036 mg/L cadmium (Cd), with Pb and Cd exceeding the National Environmental Standards and Regulations Enforcement Agency (NESREA) permissible discharge limits. However, treatment with the phytosynthesised AgNPs significantly reduced concentrations of all investigated PTEs. The highest removal efficiency of PTEs was observed in Cr (91.01%), closely followed by Pb, Cd and Cu with 79.98 %, 79.96 % and 70.05 % respectively, while Ni had the lowest at 60.08%. Also, TEM images confirmed the formation of predominantly spherical, crystalline, plant-capped AgNPs with a size range consistent with the XRD pattern. This is largely due to the organic capping agents of the *D. filix-mas* leaf extract. Finally, this result demonstrates that *D. filix-mas*-mediated AgNPs can effectively reduce and adsorb hazardous PTEs, offering an eco-friendly and sustainable treatment alternative for raw textile effluent treatment.

Keywords: *Dryopteris filix-mas*, phytosynthesis, silver nanoparticles, textile effluent, potentially toxic elements.

GRAPHICAL ABSTRACT



INTRODUCTION

The textile industry is recognised as a major source of industrial wastewater. Textile production processes such as wet processing, dyeing and finishing require large volumes of water and generate substantial quantities of wastewater [1,2]. The resulting textile effluent contains residual synthetic dyes, inorganic salts, processing auxiliaries, surfactants, and some potentially toxic elements (PTEs) [1,3]. Natural biodegradation processes do not readily break down these residual chemicals, which may persist in aquatic environments for long periods. As a result, this increases the risk of environmental contamination and exposure, creating long-term exposure for communities that depend on rivers and groundwater for drinking and irrigation [4]. Textile effluents usually contain PTEs such as chromium, lead, cadmium, copper, and zinc, which are persistent, bioaccumulative, and toxic to humans and aquatic organisms even at relatively low concentrations [5]. Due to their resistance to biological, thermal, and photochemical degradation, these PTEs persist in aquatic environments and sediments for extended periods [6]. Aside from their chemical toxicity, untreated textile effluents degrade aquatic ecosystems by reducing light penetration, disrupting microbial communities, and introducing persistent contaminants into surrounding soils and food chains [1,5].

Conventional treatment methods for textile wastewater have several limitations. Chemical coagulation generates hazardous sludge, biological treatment is inhibited by synthetic dyes, and membrane technologies are constrained by rapid fouling from dyes and suspended solids and high operational costs [1]. Consequently, the high capital and operating costs associated with these technologies can limit their adoption, particularly in resource-constrained settings [7]. High concentrations of dyes and other contaminants further reduce the efficiency of biological treatment systems by inhibiting microbial activity and clogging treatment media [8].

Recently, silver nanoparticles (AgNPs) have been widely studied for wastewater remediation due to their high surface-area-to-volume ratio, which provides abundant reactive sites for the adsorption and catalytic degradation of contaminants [9,10]. Plant-mediated AgNPs address these limitations by removing contaminants through adsorption and catalytic degradation, providing an effective treatment alternative even under conditions where biological treatment efficiency is limited [8]. Among the various green synthesis approaches, plant-mediated synthesis, often known as phytosynthesis, is an environmentally friendly and sustainable strategy for the production of silver nanoparticles [9,10]. The phytosynthetic method using plants is promising because plants contain several phytochemicals such as flavonoids, tannins, phenols, saponins, proteins, and terpenoids [11]. These phytochemicals serve as reducing and stabilising agents and have the ability to make nanoparticles with low energy requirements and non-toxic reactants [11]. Pteridophytes are vascular, seedless plants with high phytochemical properties that are very underutilised, particularly in Nigeria. Pteridophytes such as *Dryopteris filix-mas* (L.) Schott are rich in polyphenols, flavonoids, tannins, alkaloids, proteins, and other bioactive compounds, which are known to function as natural reducing and stabilising agents during AgNP synthesis [12].

While plant-mediated synthesis of silver nanoparticles has been widely reported [9,10], the use of *Dryopteris filix-mas* for textile wastewater remediation remains largely unexplored. Therefore, in this study, the potential of *D. filix-mas* was harnessed for the phytosynthesis of nanoparticles. The synthesised nanoparticles were characterised and evaluated for the removal of potentially toxic elements from textile wastewater collected from Idi-Aro, Abeokuta, Ogun State, Nigeria.

MATERIAL AND METHODS

Study Area

Raw textile wastewater was collected from a textile factory discharge channel at Idi-Aro, Abeokuta South Local Government Area, Ogun State, Nigeria (7.1654° N, 3.3445° E).

Plant sample collection and Identification

Fresh mature fronds of *Dryopteris filix-mas* (L.), commonly called male fern, were harvested from Lagos State University Botanical Garden, Ojo, Lagos, Nigeria (6.4000° N, 3.1994° E). The plant was authenticated at the Lagos State University Herbarium and assigned a voucher number LSH-001307. The plant samples were air-dried at room temperature for 14 days to reduce moisture content and prevent degradation of active phytochemicals. The dried fronds were pulverised into fine powder using a clean electric blender and stored in an airtight container for extraction.

Collection of Industrial Textile Wastewater

Raw textile wastewater was collected from a discharge channel at an active textile mill drainage line in Idi-Aro market, Abeokuta, Ogun State, Nigeria. Collection, preservation, and handling were performed in accordance with the Standard Methods for the Examination of Water and Wastewater [13]. The container was then sealed and labelled with the date and location. Samples were transported to the laboratory for baseline analysis.

Acid Digestion of wastewater sample

Wastewater samples were digested with aqua regia to solubilise metals and decompose the organic matrix before atomic absorption spectrometric analysis [13]. A 50 mL aliquot of each raw well-mixed wastewater sample was measured into a clean, acid-washed 125 mL borosilicate Erlenmeyer flask. To each sample, a 1:3 volume ratio of nitric acid (HNO_3, 65%) and hydrochloric acid (HCl, 37%) were added under a fume hood. The flasks were then heated in a water bath at 85 ± 5°C for 2 hours. After digestion, the flasks were cooled to room temperature. The mixtures were filtered through Whatman filter paper. The filtrate was transferred to a volumetric flask and made up to 50 mL with ultra-pure deionised water to account for evaporation losses. The acidified samples were stored in clean 50 mL polyethene vials and analysed for potentially toxic elements.

Analysis of Potentially Toxic Elements (PTEs) in wastewater samples

To evaluate the contamination baseline in the wastewater sample and assess the remediation efficiency of the *Dryopteris filix-mas*-synthesised AgNPs, five PTEs of interest were considered, namely: cadmium (Cd), copper (Cu), chromium (Cr), lead (Pb), and nickel (Ni) and the concentration of PTEs was measured in all the samples before and after treatment. The PTEs were analysed using a double-beam Atomic Absorption Spectrophotometer (AAS) with element-specific hollow cathode lamps according to the method described by [14]. Acid-digested samples were aspirated in triplicate into an air-acetylene flame for atomization. Reagent blanks containing the same aqua regia matrix were run with each batch to correct for baseline drift and laboratory contamination. Absorbance values were averaged from the triplicate readings, converted to mg/L, and blank-corrected.

Preparation of *Dryopteris filix-mas* Leaf Extract

The preparation of *D. filix-mas* extract was carried out as described by [12,15]. A cold aqueous maceration method was used to extract water-soluble reducing and capping compounds while minimising thermal degradation of phytochemicals. Fifty grams (50 g) of finely ground *D. filix-mas* leaf powder was placed in a clean 2000 mL borosilicate Erlenmeyer flask with 1000 mL of sterile distilled water. The mixture was macerated at room temperature for 48 hours. During this period, the flask was stirred at intervals to improve mass transfer and prevent localised saturation. After 48 hours, the slurry was filtered through Whatman No. 1 filter paper to obtain a clear, particle-free extract. The extract was stored in dark glass bottles at 4°C before being used for silver nanoparticle synthesis to limit microbial growth.

Preparation of Silver Nitrate ($AgNO_3$) and NaOH Stock Solutions

To prepare a 0.01 M solution of silver nitrate, 1.6987 g of $AgNO_3$ crystals were weighed using an analytical balance and dissolved in one litre of distilled water. The solution was prepared in an amber bottle to minimise photodegradation. A solution of sodium hydroxide (NaOH) was prepared as a pH-adjuster of the reaction mixture, and 0.400 g of NaOH pellets was gradually dissolved in 300 mL of distilled water with constant stirring [16]. The solution was then transferred to a one-litre volumetric flask, giving a concentration of 0.0333 M.

Preparation of the reaction mixture for the phytosynthesis of silver nanoparticles

The phytosynthesis of silver nanoparticles was done using the aqueous extract of *D. filix-mas*. The reaction mixture was prepared by mixing 800 mL of 0.01 M $AgNO_3$ solution with 200 mL of the plant extract in a 4:1 ratio. The mixture was transferred to a one-litre flask with a magnetic stir bar placed on a magnetic hot plate.

The mixture was stirred continuously for one hour. After five minutes of stirring, approximately 0.25 mL (five drops) of the 0.0333 M NaOH solution was added dropwise, using a plastic transfer pipette to increase the pH of the reaction mixture. The final pH of the reaction mixture was approximately 8.5. Alkaline conditions have been reported to facilitate the reduction of Ag^+ ions and promote the formation of silver nanoparticles [8]. The reaction was maintained for 1 hour, then removed from heat and allowed to cool for 15 minutes. The colloidal suspension was transferred into polypropylene centrifuge tubes and centrifuged at 3,500 rpm for 15 minutes. This was swiftly followed by resuspending the pellets in distilled water to remove water-soluble biomolecules, as described by [16]. The collected nanoparticle pellets were transferred into clean crucibles and placed in a laboratory oven set at 80°C. Drying continued for 10 hours to obtain dry, stable silver nanoparticle powder. After drying, the residual sample was weighed, and a total of 3 grams was obtained. The nanoparticles appeared as a black solid mass and were transferred into sterile plastic bottles for storage.

Characterisation of synthesised nanoparticles using ATR-FTIR

FTIR analysis was conducted using Attenuated Total Reflectance (ATR-FTIR) with a Bruker Vertex-80 spectrometer to identify the organic chemical species coating the silver nanoparticles. The dried nanoparticle samples were scanned within the 4000–400 cm^{-1} range [16].

Surface morphology and elemental composition using SEM-EDX

The surface morphology and elemental composition of the synthesised AgNPs were analysed using scanning electron microscopy and energy dispersive X-ray spectroscopy (SEM-EDX). The phytosynthesized AgNPs were imaged under high vacuum to assess particle shape, size, and degree of agglomeration. EDX spectra were collected from selected areas to confirm the presence of silver and to check for residual nitrate or other impurities [14].

Characterisation of synthesised nanoparticles using X-Ray Diffraction (XRD)

The crystal structure of the AgNPs was determined by X-ray diffraction. Patterns were recorded from $2\theta = 20°$ to 80° using Cu Kα radiation ($\lambda = 1.5406$ Å) on a Siemens D5005 diffractometer [14].

Characterisation of synthesised nanoparticles using Transmission Electron Microscopy (TEM):

TEM imaging was done on a Tecnai TF30 ST field-emission TEM at 300 kV as described by [17]. The high resolution allowed direct measurement of individual particle sizes and clear distinction between the dense silver core and the lighter organic coating from *D. filix-mas* metabolites.

Application of AgNPs for Wastewater Treatment

The application of nanoparticles for the treatment of textile wastewater was carried out according to the method described by [14]. The phytosynthesized silver nanoparticles (AgNPs) were applied to textile wastewater using a batch adsorption treatment in order to evaluate their potential for pollutant removal. The wastewater sample was filtered through Whatman No. 1 filter paper to remove suspended debris, particulate matter, and biological residues. The filtered wastewater was subsequently used for the treatment process. All adsorption tests were performed in quadruplicate to ensure reproducibility. For each test, 50 mL of filtered wastewater was placed in a 125 mL borosilicate flask and mixed with 0.2 g of dried AgNP powder. A control flask containing 50 mL of wastewater without nanoparticles was prepared under the same conditions. All flasks were shaken on an orbital shaker at 150 rpm for 2 hours at room temperature to allow contact between the dissolved metals and the nanoparticles. After 2 hours, the mixtures were centrifuged at 4,000 rpm for 20 minutes to separate the metal-loaded nanoparticles. The supernatant was filtered again through a 0.22 µm syringe filter to remove any remaining particles. The final filtrate was stored in acid-washed polyethylene vials for metal analysis by a flame atomic absorption spectrophotometer.

Percentage Removal Efficiency of PTEs by *Dryopteris filix-mas* phytosynthesized Nanoparticles

The removal efficiency of each PTE after batch treatment with *D. filix-mas* capped AgNPs was calculated using the equation below.

$$\textbf{Removal Efficiency (\%)} = \frac{(Ci - Cf)}{Ci} \times 100$$

Where:

Ci = Initial mean concentration of the PTEs in the raw wastewater (mg/L)
Cf = Final residual concentration of the PTE in the treated filtrate after treatment (mg/L)

Data Analysis

All experimental data were analysed using standard statistical methods. The results of the batch tests from the flame atomic absorption spectrophotometer were reported as Mean ± Standard Deviation from quadruplicate runs. XRD patterns were processed in OriginLab for baseline correction and peak identification, with phases confirmed against ICDD/JCPDS standards. FTIR spectra were baseline-corrected, and absorption bands were assigned based on standard functional group frequencies. TEM images were analysed to obtain particle size distributions. To test if metal removal was due to the nanoparticles and not random variation, data were analysed using a paired t-test in SPSS. Differences were considered significant at $p<0.05$.

RESULTS AND DISCUSSION

Baseline Levels of Potentially Toxic Elements in Textile Effluent

The raw textile wastewater from the Idi-Aro channel contained high concentrations of multiple potentially toxic elements (PTEs). Lead and cadmium exceeded both the National Environmental Standard Regulations Enforcement Agency (NESREA) [18] and the World Health Organisation (WHO) [19] permissible limits. In contrast, chromium exceeded the WHO guideline but remained within the NESREA discharge limit (Table 1). Similar contamination profiles have been reported for textile wastewater in southwestern Nigeria [20]. In addition, the high lead and chromium values are consistent with the environmental audits of [21], who reported heavy metal contamination associated with informal textile dyeing activities in Ogun State. The high concentrations of lead and cadmium are of particular environmental concern due to their persistence and tendency to bioaccumulate in aquatic ecosystems following continuous discharge of untreated effluents [22].

Table 1: Baseline concentrations of PTEs in raw Idi-Aro textile wastewater compared with regulatory limits

Potentially Toxic Element	Mean Measured Concentration (mg/L)	NESREA Permissible Limit (mg/L)	WHO International Guideline (mg/L)	Regulatory Compliance Status
Chromium (Cr)	0.990 ± 0.089	1.0	0.05	Non-Compliance
Lead (Pb)	0.374 ± 0.144	0.05	0.01	Severe Non-Compliance
Cadmium (Cd)	0.343 ± 0.036	0.01	0.003	Severe Non-Compliance
Copper (Cu)	0.193 ± 0.036	1.0	2.0	Compliant
Nickel (Ni)	0.026 ± 0.008	0.05	0.07	Compliant

Note: Values are from four replicate samples, n = 4

Phytosynthesis and Characterization of *Dryopteris filix-mas* AgNPs

The change in reaction colour from pale yellow to dark brown within 10 minutes was the first visual indication of Ag formation. Similar colour changes during the phytosynthesis of AgNPs have been reported previously and are attributed to localised surface plasmon resonance resulting from the reduction of Ag^{+} to Ag^{0} [1,17].

Fourier Transform Infrared Spectroscopy (FTIR) Analysis

The FTIR spectrum exhibited absorption bands at approximately 3650, 1679, and 1384 cm^{-1}, corresponding to O–H or N–H stretching, amide C=O stretching, and C–N or C–O vibrations, respectively (Figure 1). These results are consistent with the phytochemical profile reported for *D. filix-mas* leaves by [12], which identified flavonoids, phenolics and other bioactive compounds known to function as reducing and stabilising agents during plant-mediated AgNP synthesis. A shoulder around 1679 cm^{-1} corresponds to the amide band, indicating the presence of protein carbonyl groups involve in the formation of the nanoparticles [16]. These biomolecules contributed to the reduction and stabilisation of the synthesised nanoparticles through the presence of the aforementioned functional groups for protein and phytochemicals.

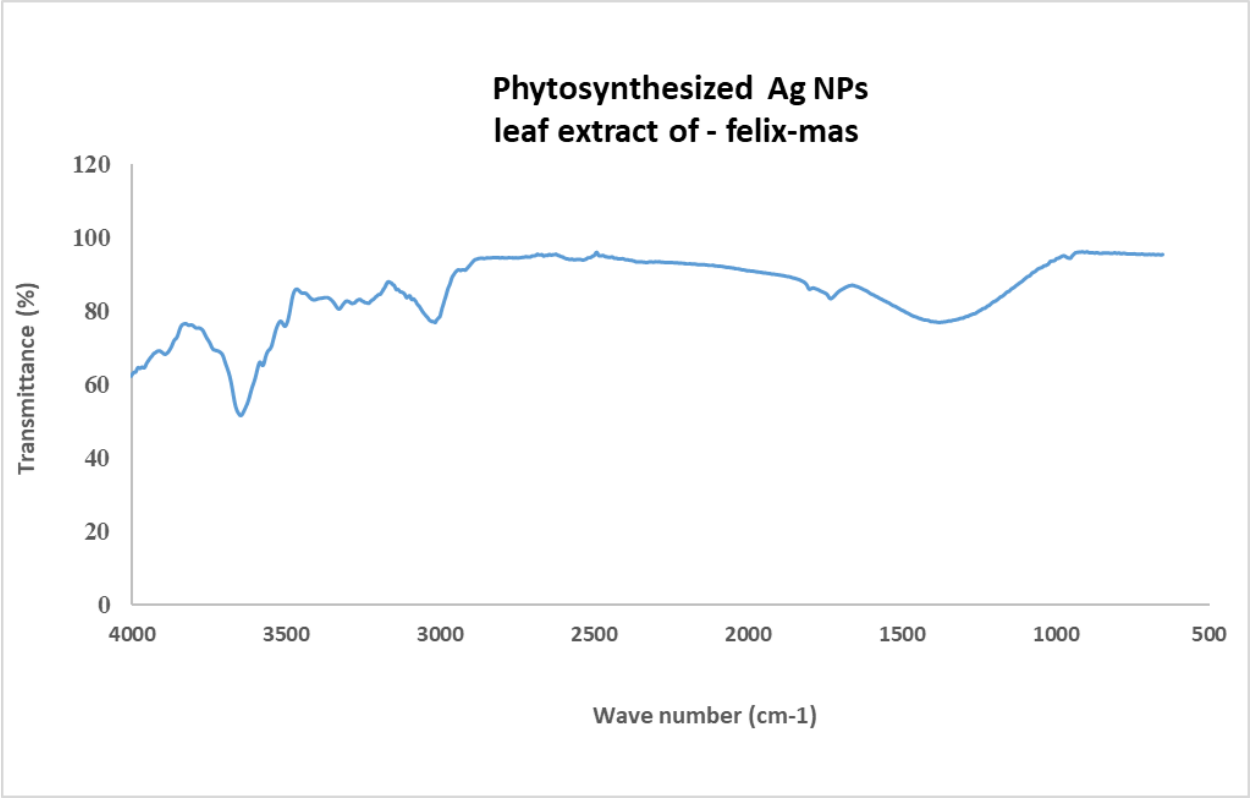


Figure 1: FTIR spectrum of AgNPs synthesized using *D. filix-mas* frond extract

Scanning Electron Microscopy (SEM) Analysis

SEM images revealed irregular aggregated structures at 100 µm and 200 µm scales, with sheet-like morphology (Figure 2). The observed aggregation is attributed to drying of the plant matrix during sample preparation, which forms a bulk film that embeds the AgNPs [23]. Furthermore, the consistent irregular shapes implies that there is a homogenous particle size distribution which could be due to magnetic interaction between the AgNPs.

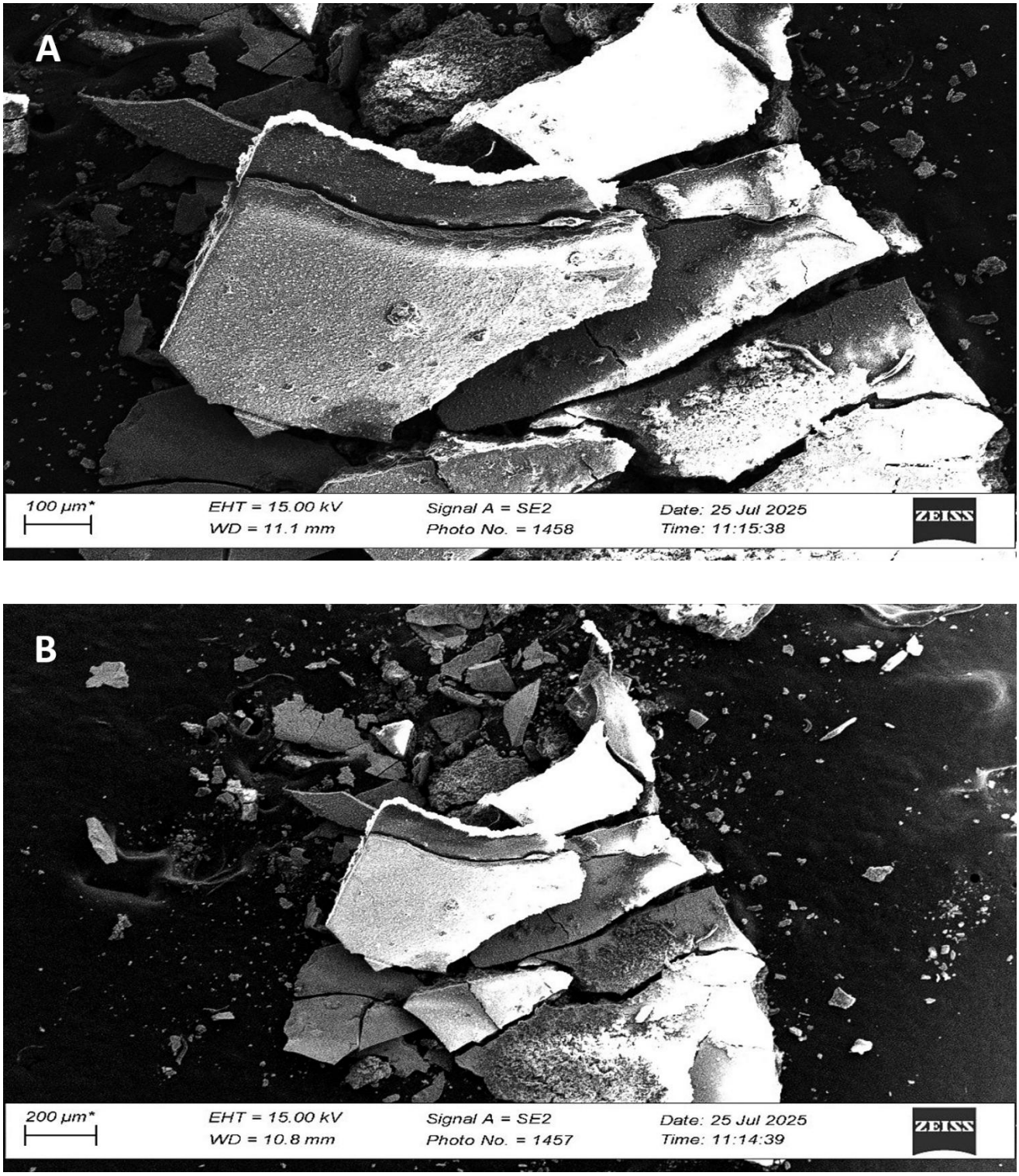


Figure 2: SEM analysis of AgNPs showing surface morphology at different Scale bars: (a) 100 µm, (b) 200 µm.

Energy Dispersive X-ray Spectroscopy (EDX) Analysis

EDX analysis confirmed the successful phytosynthesis of AgNPs. Silver was the dominant metal at 10.08% (Figure 3), while carbon and oxygen were also high at 66.45% and 21.63%, respectively (Table 2). The dominant C and O peaks correspond to organic compounds from the *D. filix-mas* extract acting as reducing and stabilising

agents [16]. Additional peaks of phosphorus, sulphur, chlorine, and potassium are attributed to plant-derived metabolites and salts, while the Ag peak at approximately 3.0 keV confirms the presence of silver.

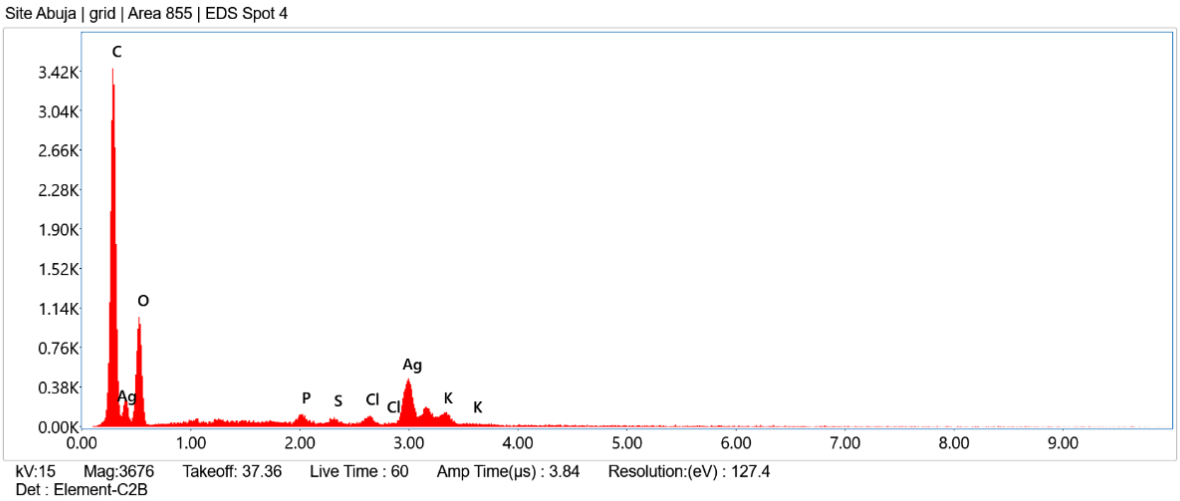


Figure 3: Energy Dispersive X-ray spectrum of phytosynthesized AgNPs showing elemental composition.

Table 2: Elemental composition of synthesised nanoparticles from EDX analysis

Element	Weight (%)	Atomic (%)
Carbon (C)	66.45	78.70
Oxygen (O)	21.63	19.23
Phosphorus (P)	0.43	0.20
Sulfur (S)	0.21	0.09
Chlorine (Cl)	0.34	0.14
Potassium (K)	0.86	0.31
Silver (Ag)	10.08	1.33

Transmission Electron Microscopy (TEM) and X-Ray Diffraction (XRD) Analysis

TEM analysis revealed that the synthesized AgNPs were predominantly spherically shaped particles with sizes ranging from 1.47 to 10.02 nm, and most particles falling between 2 and 6 nm (Figure 4). Also, a few of the particles were observed to have a thin layer of coating which may be due to the capping agents from the *D. filix-mas* extract. This size range is consistent with the XRD pattern, which showed Bragg peaks at 2θ values of 38.1°, 44.3°, 64.4°, and 77.4° (Figure 5). These positions correspond to the (111), (200), (220), and (311) planes of face-centred cubic silver, matching JCPDS Card No. 04-0783 [24]. TEM and XRD analyses collectively confirmed the formation of predominantly spherical, crystalline AgNPs using *D. filix-mas* extract.

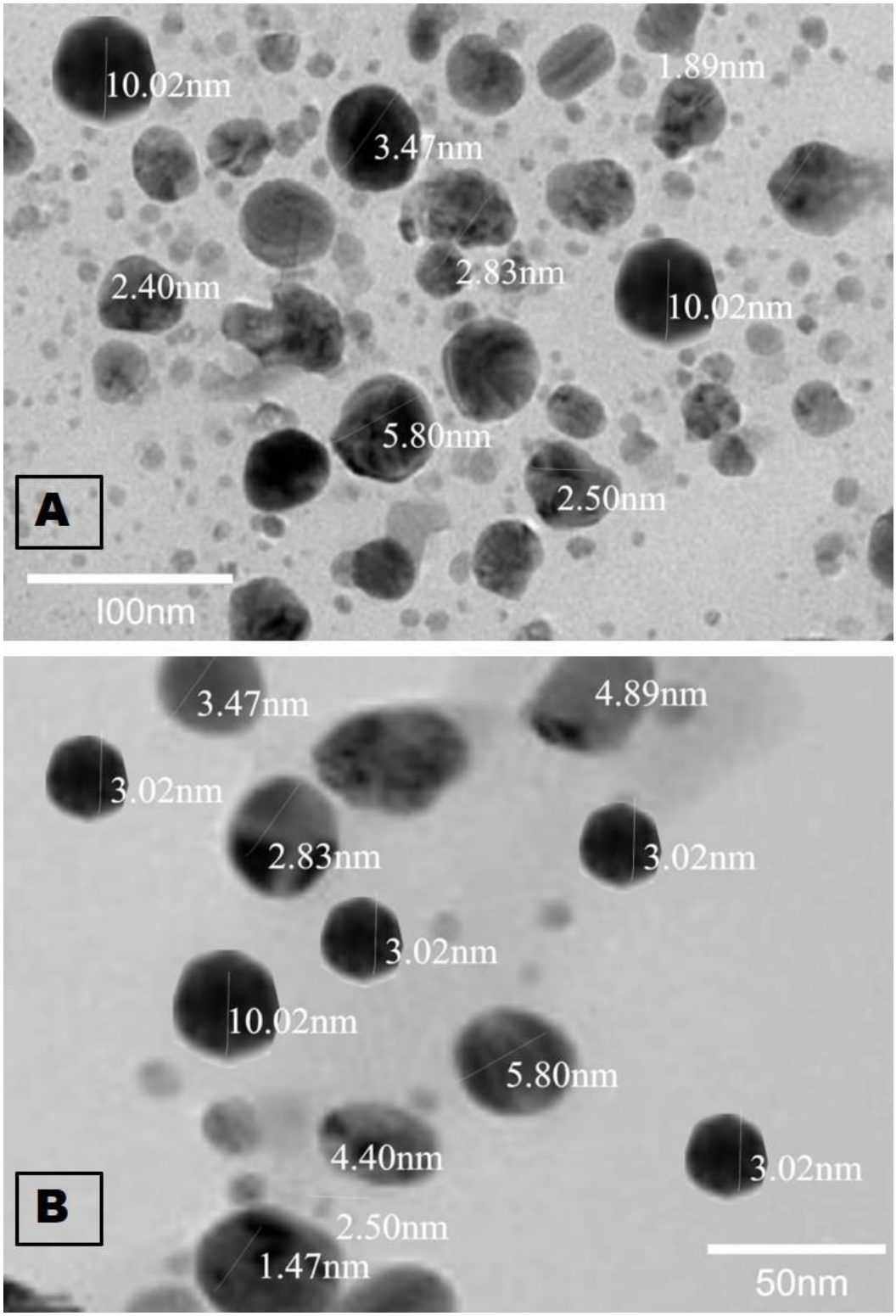


Figure 4: TEM images of AgNPs synthesized using *D. filix-mas* leaf extract showing predominantly spherical particles. Scale bars: (a) 100 nm, (b) 50 nm

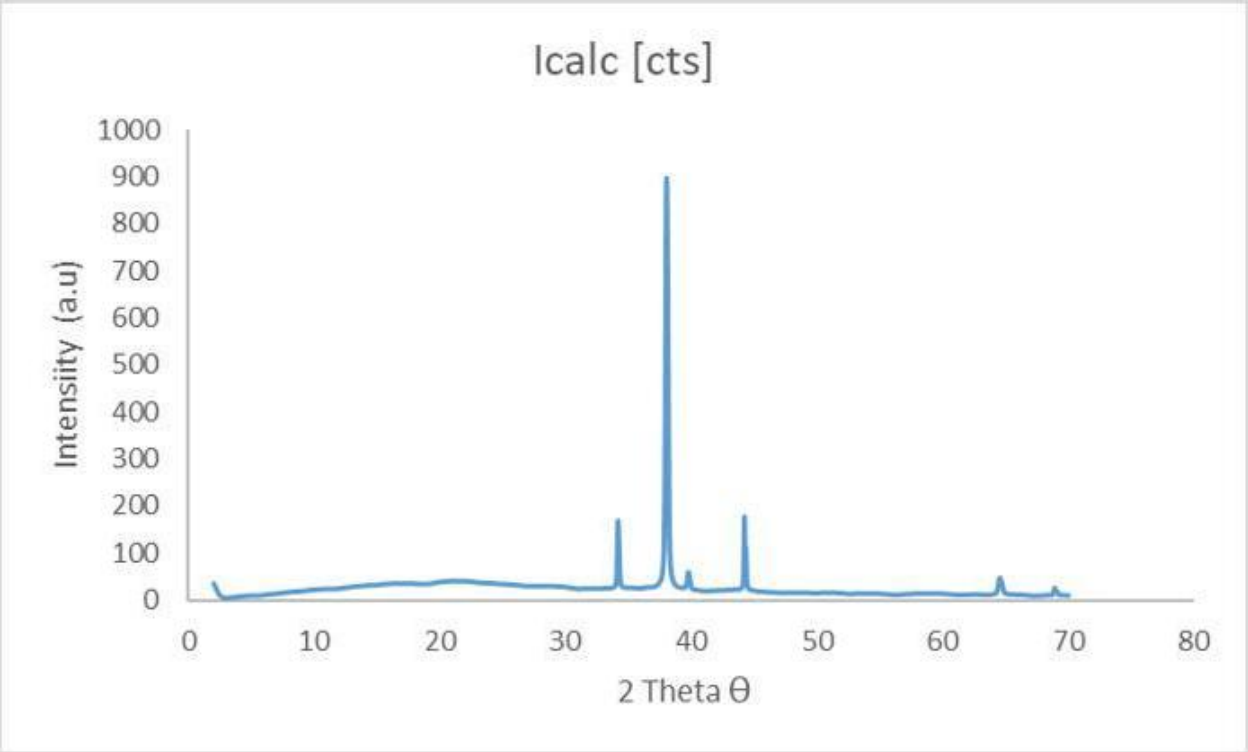


Figure 5: X-ray diffraction (XRD) pattern of AgNPs synthesized using *Dryopteris filix-mas* leaf extract.

Performance evaluation of AgNPs-treated PTEs based on their concentrations

Treatment with the AgNPs significantly reduced the concentration of all analysed potentially toxic elements (PTEs) in the textile wastewater (Figure 6). Chromium was effectively removed, with a removal efficiency of 91.01% (Table 3). The high chromium removal may be attributed to its adsorption onto oxygen-containing functional groups present on the surface of the plant-capped AgNPs. This can be corroborated by studies by [17, 23], who suggested that phytosynthesized AgNPs can facilitate the reduction of Cr (VI) to Cr (III) when hexavalent chromium is present. Copper and nickel were also substantially reduced, with efficiencies of 70.05% and 60.08%, respectively (Figure 6). Lead and cadmium gave comparable removal efficiencies of 79.98% and 79.96%, respectively. Their comparable removal efficiencies suggest similar modes of interaction with the functional groups on the nanoparticle surface. Copper and nickel had lower removal at 70.05% and 60.08%, respectively. [25] noted that synthetic surfactants and dye auxiliaries in raw textile effluent can form stable complexes with Cu^{2+} and Ni^{2+}, which may reduce their adsorption onto nanoparticle surfaces. The presence of such competing ligands may account for the lower uptake in this multi-component effluent. After 2 hours of contact, the residual concentrations complied with the applicable NESREA discharge limits for chromium, copper, and nickel, whereas lead and cadmium, although substantially reduced, remained above their respective permissible limits (Table 3). The results demonstrate that *D. filix-mas*-mediated AgNPs can effectively reduce PTE concentrations in textile wastewater, but additional treatment steps would be required to meet discharge standards for lead and cadmium.

Table 3: Potentially toxic element concentrations and removal efficiency of synthesised AgNPs across wastewater batches

Potentially Toxic Element	Pre-Treatment Raw Conc. (mg/L)	Post-Treatment Effluent Conc. (mg/L)	Calculated Removal Efficiency (%±SD)	NESREA Permissible Limit (mg/L)	WHO International Guideline (mg/L)
Chromium (Cr)	0.9900 ± 0.089	0.0890 ± 0.008	91.01 ± 0.03	1.0	0.05
Lead (Pb)	0.3740 ± 0.144	0.0748 ± 0.029	79.98 ± 0.14	0.05	0.01
Cadmium(Cd)	0.3430 ± 0.036	0.0688 ± 0.007	79.96 ± 0.08	0.01	0.003
Copper (Cu)	0.1930 ±0.036	0.0578 ± 0.010	70.05 ± 0.26	1.0	2.0
Nickel (Ni)	0.0255 ± 0.008	0.0103 ± 0.004	60.08 ± 1.48	0.05	0.07

Note: Values are from four replicate samples, n = 4

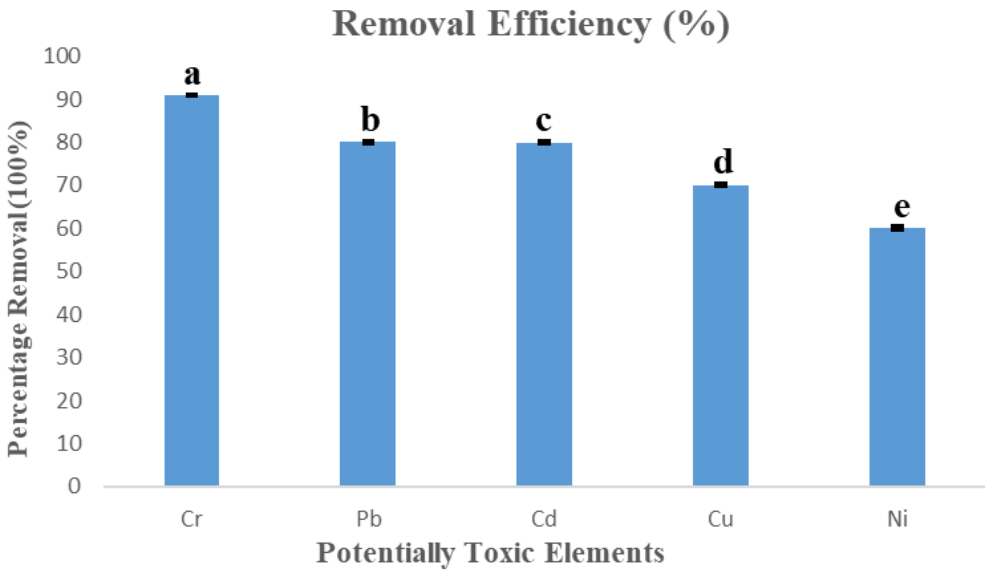


Figure 6: Percentage removal efficiency of PTEs from textile wastewater after treatment with *Dryopteris filix-mas*-capped AgNPs.

CONCLUSION

Untreated textile wastewater contained elevated concentrations of potentially toxic elements, notably lead, cadmium, and chromium, underscoring the need for effective treatment before discharge. Application of the phytosynthesized AgNPs to the raw effluent reduced the concentrations of all investigated potentially toxic elements (PTEs). The results demonstrate that *D. filix-mas*-mediated AgNPs can be applied for textile wastewater treatment, but additional optimisation may be required to improve removal efficiencies for lead and

cadmium. Overall, this study demonstrates that *D. filix-mas* is a sustainable biological resource for the phytosynthesis of AgNPs and highlights its potential for remediating textile wastewater contaminated with potentially toxic elements. Future work should focus on optimising nanoparticle regeneration and reuse, as well as validating the treatment process under pilot-scale conditions.

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CONFLICT OF INTERESTS

The authors declare no conflicts of interest related to the publication of this paper.

REFERENCES

1. Al-Tohamy R, Ali SS, Li F, Okasha KM, Mahmoud YAG, Elsamahy T, Jiao H, Fu Y, Sun J. Azo dyes biodegradation: Insights into toxicity, microbial remediation, regulation, and future perspectives. *Journal of Advanced Research*. 2022; 40:163–188. https://doi.org/10.1016/j.jare.2021.12.007
2. Azanaw A, Birlie B, Teshome B, Jemberie M. Textile effluent treatment methods and eco-friendly resolution of textile wastewater. *Case Studies in Chemical and Environmental Engineering.* 2022; 6: 100230
3. Catarino ML, Sampaio F, Gonçalves AL, Sustainable Wet Processing Technologies for the Textile Industry: A Comprehensive Review. *Sustainability*. 2025;17(7): 3041. https://doi.org/10.3390/su17073041
4. Rápó E, Tonk S. Factors affecting synthetic dye adsorption; desorption studies: A review of results from the last five years (2017–2021). *Molecules,* 2021; 26(17): 5419. https://doi.org/10.3390/molecules26154447
5. Mitra S, Chakraborty AJ, Tareq AM, Emran TB, Nainu F, Khusro A, Idris AM, Khandaker MU, Alqahtani AM, Mostafa-Hedeab G. Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity. *Journal of King Saud University - Science*, 2022; 34(3): 101865. https://doi.org/10.1016/j.jksus.2022.101865
6. Carvalho MAR, Botero WG, Oliveira LC. Natural and anthropogenic sources of potentially toxic elements to aquatic environment: A systematic literature review. *Environmental Science and Pollution Research*. 2022; 29(34): 51318–51338. https://doi.org/10.1007/s11356-022-20980-x
7. Kallawar GA, Bhanvase BA. A review on existing and emerging approaches for textile wastewater treatments: Challenges and future perspectives. *Environmental Science and Pollution Research,* 2024; 31(2): 1748–1789. https://doi.org/10.1007/s11356-023-31175-3
8. Sati A, Ranade, TN, Pratap A. Silver Nanoparticles (AgNPs): Comprehensive insights into bio/synthesis, key influencing factors, multifaceted applications, and toxicity—A 2024 update. *Life Sciences*. 2024; 342: 118867.
9. Kaur J, Kaur K, Kaur K, Matharu AS, Mehta SK. Greener aspects of nanoparticle synthesis for water remediation: Challenges and future perspective. *Advances in Environmental and Engineering Research,* 2023; 4(2): 027. https://doi.org/10.21926/aeer.2302027
10. Khan SA, Jain M, Pandey A, Pant KK, Ziora ZM, Blaskovich MAT, Shetti NP, Aminabhavi TM. Leveraging the potential of silver nanoparticles-based materials towards sustainable water treatment. *Journal of Environmental Management,* 2022; 319: 115675. https://doi.org/10.1016/j.jenvman.2022.115675

11. Villagrán C, Phytosynthetic pathways for metallic nanomaterial production using wild flora extracts. *Journal of Environmental Management*, 2024; 351: 119721.
12. Femi-Adepoju AG, Oluyori AP, Fatoba PO, Adepoju AO. Phytochemical and antimicrobial analysis of *Dryopteris filix-mas* (L.) Schott. *Rasayan Journal of Chemistry*. 2021; 14(1): 616–622.
13. American Public Health Association (APHA), American Water Works Association, & Water Environment Federation. *Standard methods for the examination of water and wastewater* 24th ed. USA: 2023.
14. Oyewole TS, Osundiya MO, Osifeko OL, Adebanjo SA, Aribidesi MO, Olaoluwa GB, Olowu RA. Green synthesis of zinc oxide nanoparticles from *Morinda lucida* leaf extract for biosorption application, kinetics, and thermodynamic studies. *Discover Chemistry*. 2026; 3:126. https://doi.org/10.1007/s44371-026-00511-0
15. Aloo SO, Ofosu FK, Daliri EBM, Oh DH. UHPLC-ESI-QTOF-MS/MS metabolite profiling of the antioxidant and antidiabetic activities of red cabbage and broccoli seeds and sprouts. *Pharmaceuticals.* 2023; 16(2): 1–15.
16. Oyewole TS, Olowu RA, Osundiya MO, Tovide OO, Akanbi PJ, Abosede SO, Ejire AA. Photocatalytic degradation studies of indigo carmine dye by green-synthesized silver nanoparticles from *Theobroma cacao* extracts. *Journal of Physical Chemistry and Biophysics.* 2025; 15:422.
17. Melkamu WW, Berekete AK. Recent advances in biogenic silver nanoparticles: Synthesis, capping layer characterization, and multifunctional environmental remediation applications. *Journal of Environmental Management*, 2021; 290: 112567. https://doi.org/10.1016/j.jenvman.2021.112567
18. National Environmental Standards and Regulations Enforcement Agency (NESREA). *National environmental (textile, wearing apparel, leather and footwear sector) regulations* (S. I. No. 34). *Federal Republic of Nigeria Official Gazette*. 2009; 96(68): B973–1011.
19. World Health Organization. *Guidelines for drinking-water quality: Fourth edition incorporating the first and second addenda*. Geneva: WHO; 2022.
20. Afolabi OO, Olajire T, Akinwumiju SA, Akinbobola E, Hassan UO. Characteristics and health risk parameters of wastewater from a textile factory in southwestern Nigeria. *Journal of Innovative Research in Life Sciences.* 2022; 4(2): 45–56.
21. Babayemi JO, Ogundiran MB, Osibanjo O. Overview of environmental contamination and management of hazardous wastes from informal industrial sectors in Nigeria. *Environmental Science and Pollution Research.* 2017; 24(3): 2134–2148.
22. Jolaosho TL, Elegbede IO, Ndimele PE, Falebita TE, Abolaji OY, Oladipupo IO, Ademuyiwa FE, Mustapha AA, Oresanya ZO, Isaac OO. Occurrence, distribution, source apportionment, ecological and health risk assessment of heavy metals in water, sediment, fish and prawn from Ojo River in Lagos, Nigeria. *Environmental Monitoring and Assessment*. 2024; 196(2): 109. https://doi.org/10.1007/s10661-023-12148-y
23. Islam MS, Kumar R, Mohammadi A. Adsorption of chromium (VI) from synthetic and real tannery and textile wastewater streams using low-cost biological matrices. *Separation and Purification Technology*. 2023; 310: 114782.
24. Vizitiu DE, Drăghiceanu, OA, Popescu M. X-ray diffraction tracking and phase purity verification of biogenic face-centered cubic silver nanoparticles. *Materials Letters*, 2022; 315: 131942. https://doi.org/10.1016/j.matlet.2022.131942

25. Santhosh B, Prasad N, Sharma V. Heavy metal complexes and stabilizers in textile effluent: Persistence dynamics and impacts on microbial biodegradation. *Journal of Hazardous Materials*. 2025; 462: 132145.