

RESEARCH PAPER

Characterization and Efficiency of Green Synthesized Silver Nanoparticles Using *Spirulina Platensis* for the Abiotic Removal of Polycyclic Aromatic Hydrocarbons (PAHs) from Contaminated Soil

Abeer Abdul Rahman Hanoon Al-Saeedi *, Khitam Abbas Marhoon

Department of Environment, College of Science, University of Al-Qadisiyah, Iraq

ARTICLE INFO

Article History:

Received 27 March 2026

Accepted 19 June 2026

Published 01 July 2026

Keywords:

Abiotic Removal

Contaminated Soil

Green synthesizes

PAHs

Spirulina platensis

Silver Nanoparticles

ABSTRACT

This study was conducted in the Environmental Research Laboratory of the Department of Environment/College of Science/University of Al-Qadisiyah. The study aimed to evaluate the efficiency of silver nanoparticles (AgNPs) synthesized in the green method using the extract of spirulina algae (*Spirulina platensis*) in the abiotic decomposition and removal of polycyclic aromatic hydrocarbons (PAHs) from the soil. These compounds are considered one of the most dangerous environmental challenges due to them being persistent and highly toxic organic pollutants in the environment. This study included compounds (Anthracene, Fluoranthene, Chrysene). The prepared nanoparticles were characterized using ultraviolet and visible spectroscopy (UV-Vis) and X-ray diffraction (XRD) techniques. Scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FTIR), all of which confirmed the formation of spherical silver nanoparticles with a high-purity crystalline structure. The study included treating artificially polluted soil using three concentrations of nano-silver (0.1, 0.01, 0.001) mg/L. The treatment took place over two periods of 7 and 14 days. The treatment results showed a noticeable variation in the removal rates depending on the nano concentration and the treatment period. The highest rates of pollutant removal were recorded at a concentration of 0.1 mg/L. The study concludes that the green manufacturing of silver nanoparticles using spirulina algae represents an effective, fast, and environmentally friendly technology for treating soils contaminated with PAHs.

How to cite this article

Abdul Rahman Hanoon Al-Saeedi A, Abbas Marhoon K. Characterization and Efficiency of Green Synthesized Silver Nanoparticles Using *Spirulina Platensis* for the Abiotic Removal of Polycyclic Aromatic Hydrocarbons (PAHs) from Contaminated Soil. J Nanostruct, 2026; 16(3):4004-4015. DOI: 10.22052/JNS.2026.03.084

INTRODUCTION

Industrial expansion and increasing human activities in recent years have led to increasing global concerns due to soil contamination with persistent organic pollutants that threaten human

health and ecosystems [1]. Polycyclic aromatic hydrocarbons (PAHs) are considered among the most dangerous organic pollutants due to their high chemical stability, high ability to bioaccumulate [2], and their toxic and carcinogenic effects [3].

* Corresponding Author Email: abeer.abdulrhman@qu.edu.iq



These compounds mainly form from incomplete combustion processes of organic materials such as fossil fuels, oil spills and industrial emissions, leading to soil, water and air pollution, especially in urban and industrial areas [4]. Traditional techniques for treating contaminated soils, such as heat treatment, excavation and landfilling, or chemical oxidation, are expensive and may cause the formation of more harmful and toxic byproducts [5]. Therefore, the need has emerged for effective and innovative solutions such as environmental nanotechnology as a sustainable solution [6], because nanoparticles possess unique properties such as a high surface area that increases the reaction efficiency and high adsorption of organic pollutants [7]. However, methods for preparing nanoparticles, such as traditional chemical and physical methods, rely on the use of toxic chemicals and complex operating conditions, which limits their use in environmental applications. Hence, the importance of the green synthesis technology for nanoparticles using living organisms or plant and algae extracts has emerged as a safe, effective and more sustainable alternative, in addition to the low cost [8]. Silver nanoparticles (AgNPs) are considered one of the most widely used nanomaterials in environmental treatments due to their distinct physical and chemical properties and their ability to adsorption and surface catalysis [9]. *Spirulina platensis* algae is also an ideal choice for preparing nanoparticles because it contains bioactive compounds such as proteins, carbohydrates, antioxidants, and pigments that act as powerful reducing and stabilizing agents for the resulting nanoparticles [10].

This study aims to prove the efficiency of applying silver nanoparticles prepared biologically using spirulina algae extract in removing PAHs from contaminated soil, and to evaluate the effectiveness of these particles through abiotic adsorption processes and to understand the mechanisms of interaction between them and PAHs, in addition to knowing the extent to which the time factor and the concentration of nanoparticles affect the removal efficiency.

MATERIALS AND METHODS

Soil collection and preparation

Soil samples were collected from one of the areas in Al-Diwaniyah Governorate from a depth ranging between (0-20) cm and transported to

the laboratory in sterile containers. Impurities were removed mechanically and then sieved using a sieve with holes with a diameter of 2 mm to ensure homogeneity. It was dried in air at room temperature for 24 hours, after which the soil was sterilized using an autoclave at a temperature of 121°C for 20 minutes on two consecutive days for the purpose of completely eliminating microorganisms and heat-resistant spores [11]. After sterilization was completed, the soil was left to cool in a well-ventilated place and was kept in tightly closed, sterile containers and stored in a dark, dry place until use in subsequent experiments [12].

Artificial soil contamination with PAHs

The soil was artificially polluted with PAHs using the pollutants Anthracene, Fluoranthene, and Chrysene to obtain a typical concentration of 500 mg PAHs per kg of soil [13]. 100 mg of the pollutants were dissolved in 100 ml of Hexane solvent to obtain a homogeneous solution, then gradually added to 200 g of soil with continuous mixing to ensure homogeneous distribution of the pollutants within the soil matrix. . Place the contaminated soil mixture inside the laboratory ventilation system (fume hood) with daily stirring until the soil dries completely and the organic solvent evaporates before starting treatment.

Green synthesis of silver nanoparticles (AgNPs) of Spirulina algae

The aqueous extract of spirulina algae (*Spirulina platensis*) was prepared based on previous protocols with some minor modifications [14][15], where the algae was washed with plain water first to remove dust and impurities, then washed several times with deionized water, air-dried in the dark at room temperature until a constant weight was reached, then ground to obtain a fine powder. Weigh 15 g of the powder and add 100 ml of deionized water to it in a sterile glass beaker. Heat the mixture on a water bath at a temperature of (70-80) C with continuous stirring for 30 minutes without reaching the boiling point. Then it was filtered using Whatman No.1 filter paper and centrifuged at a speed of 8000 rpm for 15 minutes to obtain the clear aqueous extract.

AgNPs were prepared using the green synthesis method, where 5 ml of algae extract was gradually added to 50 ml of AgNO₃ silver nitrate solution at a concentration of 1 mM in a sterile glass beaker,

and the pH was adjusted to the required value (8), then the mixture was heated to 80 °C for 30 minutes with continuous stirring. It was observed that the color of the solution gradually changed from colorless to dark brown, which indicates the formation of silver nanoparticles as a result of the reduction of silver ions (Ag^+) to metallic silver (Ag^0) by the active bioactive compounds present in the algae extracts. After the synthesis process was completed, the colloidal suspension was left to gradually cool to room temperature, and then stored in sterile, tightly sealed dark glass bottles at a low temperature until used in subsequent experiments.

Characteristics of silver nanoparticles

The physical and chemical properties of silver nanoparticles prepared using spirulina algae extract were characterized based on a number of analytical techniques, including ultraviolet-visible spectroscopy (UV-Vis), scanning electron microscope (SEM), X-ray diffraction (XRD), and Fourier transform infrared analysis (FTIR), in order to confirm the formation of the nanoparticles and determine their structural and morphological properties.

Design of treatment and pollutant extraction experiment

The experimental design included three concentrations for each treatment and three replicates for each concentration. A colloidal suspension of silver nanoparticles with an initial

concentration of 500 mg/L was used as a mother solution. The dilution process was conducted to prepare three different concentrations, namely 0.1, 0.01, and 0.001 mg/L, using deionized water under sterile laboratory conditions. 100 g of contaminated soil was weighed and placed in suitable sterilized containers. 10 ml of one of the prepared nanosilver concentrations was added to each soil sample, and the soil was then mixed well to ensure homogeneous distribution of the colloidal suspension within the sample. Soil moisture was adjusted to close to field capacity using deionized water when needed. The treated soil samples and the control treatment (untreated contaminated soil) were incubated at room temperature for a period ranging from (1-14) days, with periodic stirring to ensure aeration and homogeneity of the treatment. For extraction, 10 g of each soil sample was taken, then 10 ml of hexane solvent was added to it, and the samples were shaken using a mechanical shaker for 60 minutes to ensure the extraction of PAHs.

Extraction was performed twice under the same conditions to ensure extraction efficiency. The filtrate was then separated using Whatman No. 2 filter paper and filtered a second time using a filter connected to a 0.22 micrometer medical syringe to obtain a clear, plankton-free extract. After that, the extract was concentrated using a rotary evaporator to a final volume of 5 ml, then the extract was stored in dark glass vials at 4 °C until analysis by GC-MS.

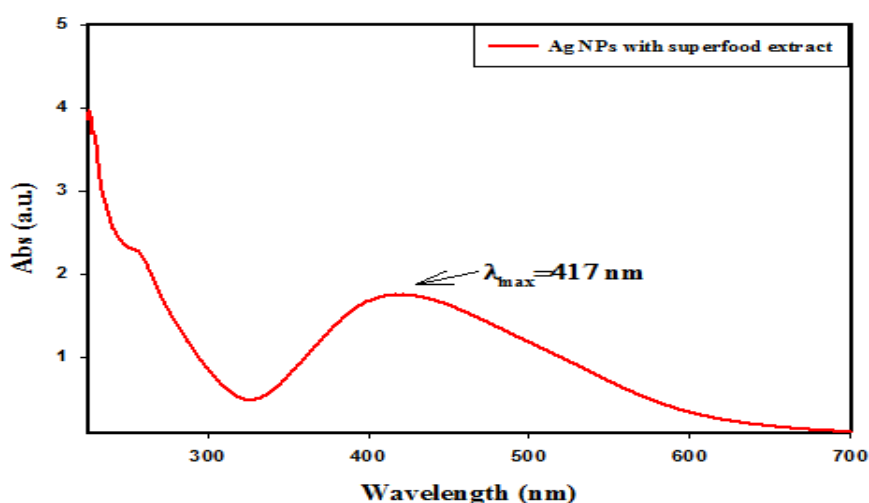


Fig. 1. UV-Vis spectrum of Ag NPs Spirulina extract.

Quantitative analysis by GC-MS

Residual PAHs in soil extracts were determined using a gas chromatograph-mass spectrometer (GC-MS) of Japanese origin. It is equipped with an automatic identification unit [AOC-20i+s] for compounds. 1 microliter of sample was taken and injected into the device, and the temperature of the ion source and interface was 250 and 230 °C, respectively. The temperature of the column oven was set at 70 °C at the beginning of operation with a holding time of 2 minutes, then the temperature was raised at a rate of 10 °C/min to reach 290 °C with a setting time of Final installation took 15 minutes. The compounds were identified based on the interpretation of the GC-MS mass spectrum and detention times, and matching them with the database of the National Institute

for Standardization and Technology (NIST), which contains more than 62,000 known patterns, to confirm the name, molecular weight, and molecular structure of the compounds measured by the device, and to evaluate the extent of their reduction as a result of biodegradation processes. The percentage of biodegradation (%) $\text{CO-Ct} / \text{CO} \times 100$ was calculated based on the results of the analysis with the GC-MS device, and these values were used to compare the efficiency of different treatments in reducing the concentrations of petroleum hydrocarbon pollutants in the soil.

RESULTS AND DISCUSSION

Characterization of silver nanoparticles (AgNPs) of spirulina extract

Ultraviolet and visible (UV-Vis) spectrum of silver

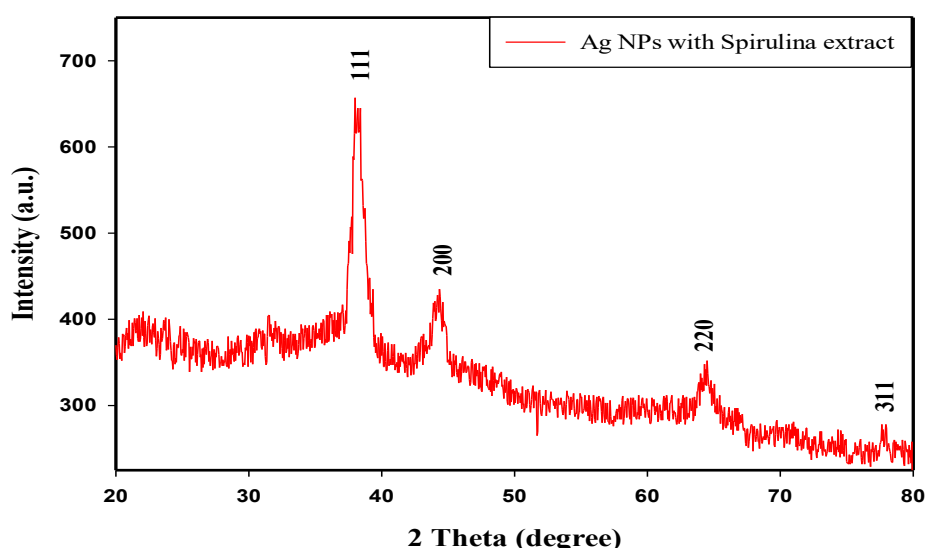


Fig. 2. X-ray diffraction (XRD) pattern of Ag NPs Spirulina extract.

Table 1. X-ray diffraction data and crystal sizes of silver nanoparticles synthesized by Spirulina extract.

2θ (°)	d (nm)	FWHM (°)	Crystal Size XS (nm)	Miller Indices (hkl)
38.192	0.23545	0.783	10	(111)
44.114	0.20512	0.637	13	(200)
64.303	0.14475	0.583	16	(220)
77.940	0.12248	0.306	35	(311)

nanoparticles prepared using spirulina extract

The UV-Vis results showed Fig. 1 the UV-Vis absorption spectrum of silver nanoparticles manufactured using spirulina extract, which shows a well-defined surface plasmon resonance (SPR) band centered at approximately 417 nm, which is a distinctive optical sign of the formation of silver nanoparticles [16]. The presence of this distinct SPR peak confirms the occurrence of efficient bioreduction of Ag^+ silver ions and generation of metallic silver nanoparticles. The broad nature of the plasmon band indicates a moderate size distribution, as well as possible variations in shape (morphology), which is often encountered in green manufacturing methods due to the complex nature of the biomolecules used. The high level of absorption in the UV region (below 300 nm) can be attributed to various organic functional groups as well as to pigment-related compounds derived from the spirulina extract, which act as simultaneously reducing and stabilizing agents. The absence of significant shift of the peak towards higher wavelengths also indicates minimal agglomeration (aggregation) as well as good stability of the prepared nanoparticles [17].

X-ray diffraction pattern (XRD) of nano-silver prepared from spirulina extract

As for the X-ray diffraction (XRD) data for silver nanoparticles prepared using spirulina extract, they show major diffraction peaks at 2θ values of 38.19° , 44.11° , 64.30° , and 77.94° , as shown in Fig. 2. These peaks are characteristic of the face-centered cubic crystal structure (FCC) of metallic silver, and can be assigned to the (111), (200), (222), and (311) crystal planes, respectively.

The highest relative density (100%) was recorded at an angle of 38.19° , indicating preferential growth at the (111) plane [18]. The peak width at half maximum (FWHM) values recorded show significant amplitude at the peaks, indicating small crystalline size. The calculated crystallite sizes (XS) ranged approximately from 10 to 35 nm, confirming the nanostructure of the particles as shown in Table 1.

The low background and clear peaks also reflect good purity and clear crystallinity, indicating that the bioactive compounds in the extract played an effective role as reducing and stabilizing agents during the green preparation of nanoparticles [19].

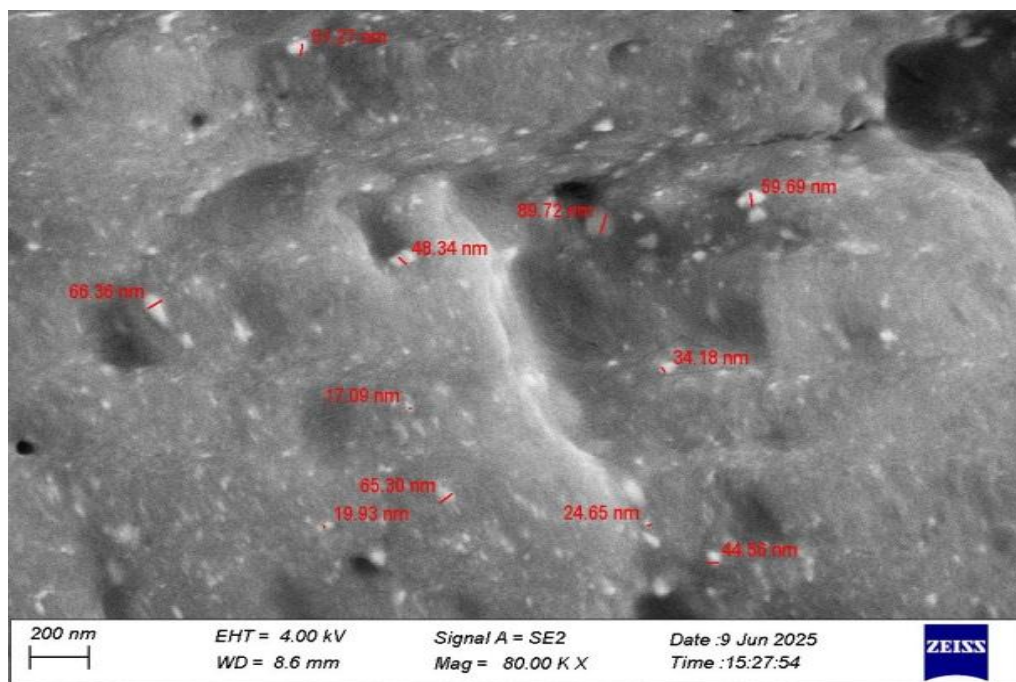


Fig. 3. Scanning electron microscope (SEM) images of prepared nano-silver spirulina at magnification (x80000) and with a tape measure of 200 nm.

SEM of AgNPs prepared using *Spirulina alga*

The SEM results showed that the nanoparticles prepared using spirulina algae extract (Fig. 3) were characterized by a dense nanostructure with a close distribution of particles and the appearance of clear porosity and voids between the particles, which indicates the formation of a surface with a high surface area. The size range of these particles ranged between 19.3–55.1 nm, and the average particle size was 33.9 nm. The high surface area and close distribution indicate a very high efficiency of the biological compounds in spirulina in the reduction process, controlling particle growth and preventing them from clumping too much, which produced smaller and more effective particles. These results are consistent with previous studies that used *Spirulina platensis* in the preparation of silver nanoparticles, which indicated the formation of particles in the range of 20–70 nm with a relatively porous structure resulting from the nature of the biological compounds in the extract [20].

These results are consistent with previous studies on the green synthesis of nanoparticles, which confirmed that the nature of the biocomposites and the preparation conditions critically control the morphological and size properties of the particles [21]. These morphological characteristics are of great importance in explaining the environmental performance of nanoparticles,

especially in applications for removing complex organic pollutants from soil.

Spirulina FTIR of AgNPs

The Fourier transform infrared (FTIR) spectrum of silver nanoparticles prepared in the presence of spirulina extract reveals different distinct peaks corresponding to the biologically active functional groups that participate in the reduction and stabilization process, Fig. 4, Table 2. The band in the 3427 cm^{-1} range is due to the presence of O–H and N–H tensions. The peaks observed at 2916 and 2852 cm^{-1} can be attributed to the C–H tension of the aliphatic compounds. The intense beam at about 1552 cm^{-1} is due to the vibration of the amide II beam. The presence of this band confirms that proteins act as capping agents. The band at about 1382 cm^{-1} belongs to the carboxyl functional groups. Intense bands in the range $1238\text{--}1037\text{ cm}^{-1}$ can be assigned to C–N and C–O–C tensions. Beams in the low frequency range below 620 cm^{-1} can be mapped to Ag–O/Ag–N tension [22].

PAHs removal efficiency

Results of analysis of soil samples contaminated with PAHs after 7 days of treatment

Silver nanoparticles prepared from spirulina algae extract showed high efficiency in removing polycyclic aromatic hydrocarbons from contaminated soil, which included anthracene,

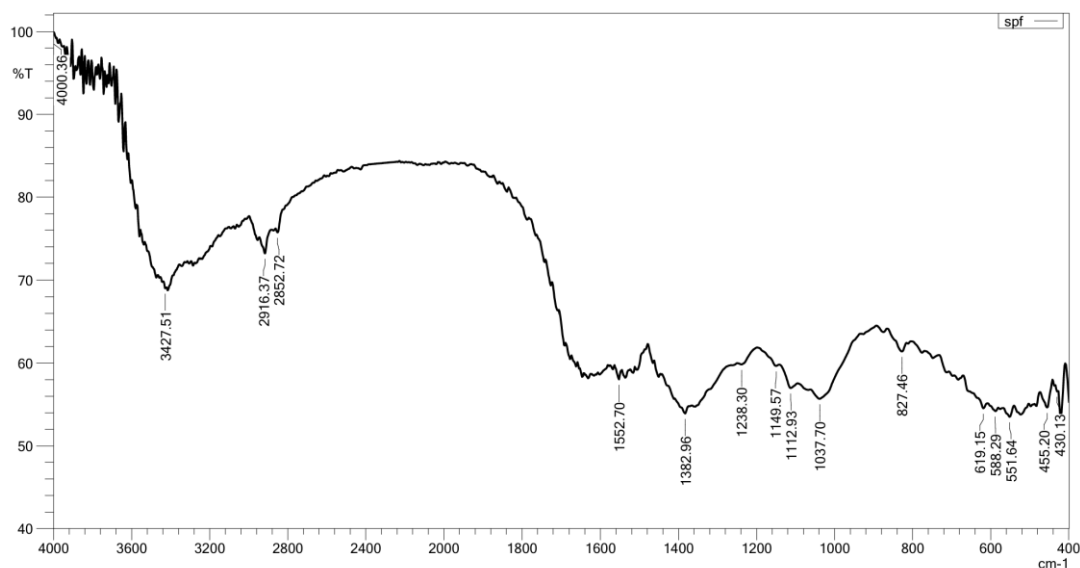


Fig. 4. FTIR of Ag NPs prepared using *Spirulina algae*.

fluoranthene, and chrysene compounds. The results showed a decrease in the concentrations of the compounds after analyzing the contaminated soil after 7 days of treatment compared to the control treatment, using GC-MS technology.

The results in Table 3 indicate a decrease in the concentration of the anthracene compound at all concentrations of nanoparticles used, as the concentrations reached 6.8, 3.16, and 1.01 mg/L

at concentrations of 0.001, 0.01, and 0.1 mg/L, respectively, compared to the control treatment (13.14 mg/L), with a removal percentage of 61.70%, 76.00%, and 92.30%. The results of the least significant difference value (LSD = 0.031 for concentration and 0.528 for removal percentage) indicate that the differences between the treatments and the control treatment were significant, and indicate a high efficiency of

Table 2. FTIR characterization of silver nanoparticles prepared using *Spirulina* alga.

Peak Position (cm ⁻¹)	Functional Group	Chemical Bond	Interpretation
3427	Hydroxyl / Amine	O-H / N-H	Broad stretching band from phenols, proteins, and polysaccharides; responsible for reduction and capping
2916	Aliphatic	C-H	Asymmetric stretching of aliphatic chains from lipids/proteins
2852	Aliphatic	C-H	Symmetric C-H stretching vibration
1552	Amide II	N-H / C-N	Protein-related band indicating peptide linkage and biomolecule adsorption
1382	Carboxylate	COO ⁻	Symmetric stretching of carboxyl groups from organic acids
1238	Amine / Ether	C-N / C-O	Nitrogenous compounds and polysaccharide structures
1149	Alcohol / Ether	C-O	C-O stretching of carbohydrates
1112	Alcohol	C-O	Secondary alcohol or glycosidic linkage vibration
1037	Polysaccharide	C-O-C	Glycosidic bond vibration in sugars
827	Aromatic C-H	=C-H	Out-of-plane aromatic bending
619	Metal-Oxygen	Ag-O	Silver-oxygen interaction on nanoparticle surface
588	Metal-Ligand	Ag-O	Binding between AgNPs and oxygenated biomolecules
551	Metal-Ligand	Ag-N / Ag-O	Coordination with proteins or amino groups
455	Lattice / Metal-O	Ag-O	Low-frequency metal-ligand vibration
430	Lattice vibration	Ag-O	Characteristic Ag-O surface interaction

nanoparticles in removing pollutants, especially at the higher concentration.

As for Fluoranthene, it decreased to 10.38, 7.23, and 4 mg/L compared to the control treatment, 20.50 mg/L, with removal rates of 49.37%, 64.70%, and 80.48%, respectively. Compared with the value of the least significant difference (0.051 (LSD for concentration and 1.086 for removal percentage), it was found that there were significant differences

between the values of the treatments, control, and different concentrations). This indicates a high efficiency in removing pollutants, which is directly proportional to the increase in the concentration of nanoparticles.

While the Chrysene compound showed the lowest removal rates compared to the Anthracene and Fluoranthene compounds, the removal rates reached 41.60%, 51.60%, and 70.70% at

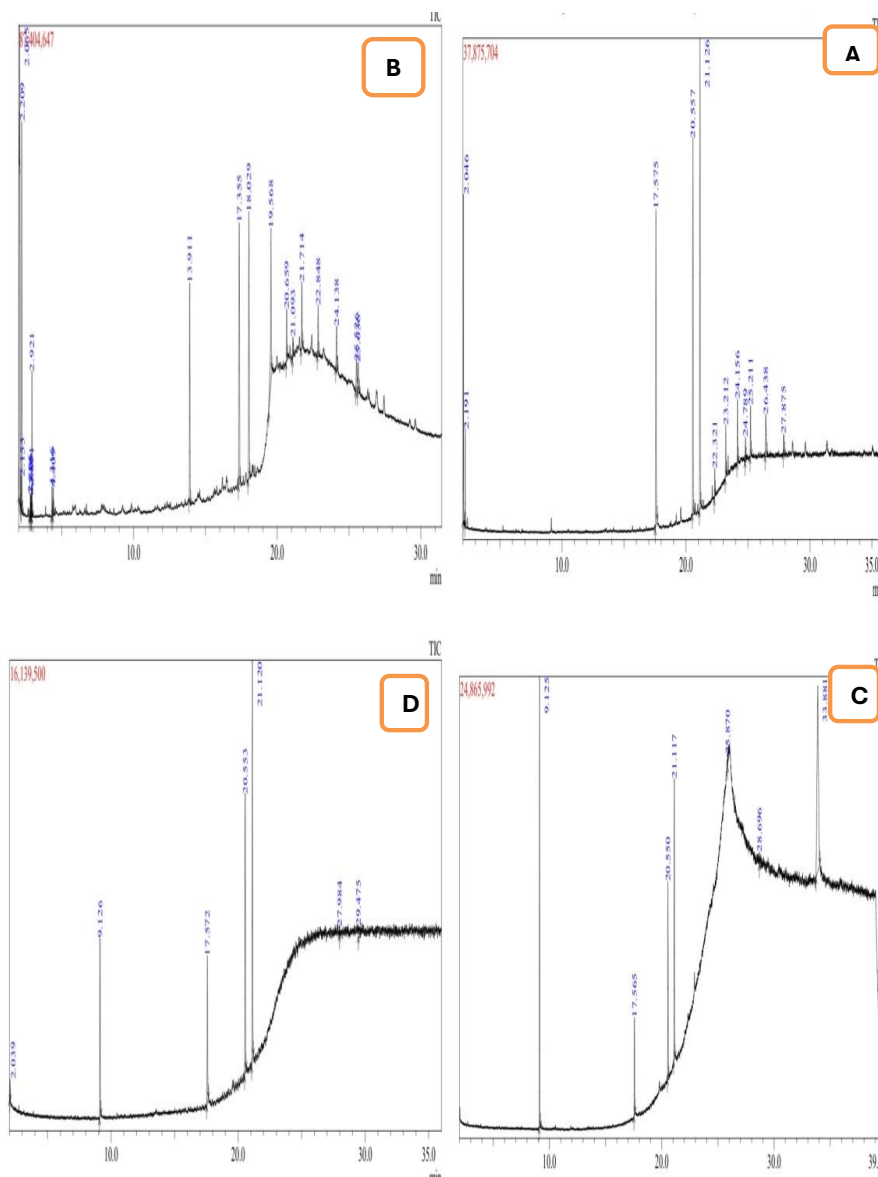


Fig. 5. Gas chromatography GC-MS diagrams showing the efficiency of silver nanoparticles bio-prepared by *Spirulina alga* at different concentrations to remove PAHs from contaminated soil (A) Control treatment (B) Concentration 0.1 mg/L (C) Concentration 0.01 mg/L (D) Concentration 0.001 mg/L.

concentrations of 0.001, 0.01, and 0.1 mg/L, respectively, compared to the control treatment of 10.38 mg/L. The LSD values of 0.062 (for concentration and 0.998 for removal percentage) indicate the presence of Significant differences between different treatments and concentrations.

The noticeable increase in the efficiency of removing compounds with an increase in the concentration of nano-silver is attributed to several factors, the most important of which is the increase in the number of effective nanoparticles, which leads to an increase in the specific surface area available for adsorption and reaction processes. Increasing the concentration also enhances the production of reactive oxygen species (ROS), which play an important role in oxidizing polycyclic aromatic hydrocarbons and breaking them down into simpler, less toxic compounds.

These results are consistent with the findings of Chakravarty et al. [23] in their study on anthracene removal using nanoparticles prepared in a green way, where they confirmed the high ability of these particles to break down anthracene rings and transform them into less toxic compounds. These results are also consistent with the findings of Abbas and others [24] in their study on the use of silver particles prepared in green ways to remove aromatic hydrocarbons, where they confirmed that the removal efficiency increases directly with the increase in the concentration of the nanomaterial.

Algae such as *Spirulina* provide proteins,

enzymes and biological compounds that enhance the stability of particles and increase their catalytic activity. This synergy improves the properties of nano-silver in terms of size, distribution and stability, thus increasing its efficiency in removing contaminants. This was supported by the study of Rajput et al. [25] who indicated that the synergistic effect of algal extracts leads to the production of nanoparticles that are more stable and effective in cleaning the environment. The results are also consistent with the study of Fahim et al. [26] which confirmed that green synthesis methods give the particles superior physical and chemical properties that enhance their performance in treating PAHs pollutants. However, the current study showed superiority in the speed of removal. The percentage reached 90.20% in just one week, which is a short period of time compared to previous studies that used traditional bioprocessing techniques that may take weeks to reach the same results. The results of this study indicate that there is an inverse relationship between the number of aromatic rings and the speed of initial decomposition. The compounds with the lowest number of rings had a very high percentage of removal within 7 days of treatment, while the tetracyclic compounds were still in the stage of active degradation, which proves that silver nanoparticles operate by a selective mechanism that is affected by the molecular weight of the pollutant in its early stages. The result of this comparison is consistent

Table 3. Effect of nano-silver of *Spirulina* extract at different concentrations (mg/L) on the concentration and percentage of PAHs removal in soil after 7 days of treatment using GC-MS technology.

Compound	Control (mg/L)	Con. 0.001 (mg/L)	Con 0.01 (mg/L)	Con. 0.1 (mg/L)	LSD P<0.05
		mean± SD R. %	mean± SD R. %	mean± SD R. %	
Anthracene	13.14	6.8±1.775	3.16 ± 0.006	1.01± 0.012	0.031
		61.70%	76.00%	92.30%	0.528
Fluoranthene	20.50	10.38±0.01	7.23 ± 0.015	4 ± 0.012	0.051
		49.37%	64.70%	80.48%	1.086
Chrysene	10.38	6.06±0.01	5.05 ±0.02	3.04 ±0.02	0.062
		41.60%	51.60%	70.70%	0.998

Mean ± SD values represent (mean ± standard deviation) the estimated residual concentration of PAHs (mg/L), and R.%. The percentage removal of the compound and LSD (P<0.05) represents the least significant difference at the 5% probability level

with what was mentioned in previous studies [27] and [28] that the efficiency of nanocatalysts is directly affected by the molecular weight and ring structure of the organic pollutants.

The efficiency of the prepared silver nanoparticles in removing PAHs after 14 days of treatment

The results of analyzing the samples with a GC-MS device after an incubation period of 14 days showed high efficiency of silver nanoparticles in bioremediation, as the absorption peaks of the compounds under study (anthracene, fluoranthene, and chrysene) completely disappeared from the chromatographic chart for all treatments and at various concentrations. Reaching the 'area under the curve' to zero indicates achieving a high removal rate of 100%, which means that the pollutants are completely decomposed or completely transformed into simple intermediate products or basic metals (CO₂ and H₂O) below the detection limit (Fig. 6).

Despite the absence of the main chromatographic peaks, mass spectrometry analysis after 14 days showed the presence of fragments of very simple compounds, such as aminoguanidine, methylurea, and propanoic acid, in addition to nitrogenous compounds such as N-nitrosodimethylamine.

The appearance of these nitrogenous

molecules and simple organic acids reflects the stage of complete mineralization that the reaction has reached. The rings of the polycyclic aromatic hydrocarbon compounds under study disintegrated completely, which confirms that the complete elimination of pollutants was not the result of adsorption only, but rather a result of the breakdown of the complex aromatic structure into simple molecules below the detection limit for the main peaks.

This is due to the fact that biologically prepared silver nanoparticles possess high chemical stability. Its activity did not stop after the first week, but rather continued its catalytic action until the soil was completely cleansed, thanks to the role of bio-capping agents extracted from algae that prevented the agglomeration of particles and maintained their surface activity.

The study confirms that the used "green nano" technology has a comprehensive disinfection capacity that exceeds the barriers of molecular weight and structural complexity of persistent organic pollutants. While the type of compound was the decisive factor in the speed of removal during the first week, the "catalytic continuity" factor became decisive in the second week, which ultimately led to the complete purification of the soil from all forms of aromatic hydrocarbons under study. These results are consistent with what previous studies indicated [29], as these studies

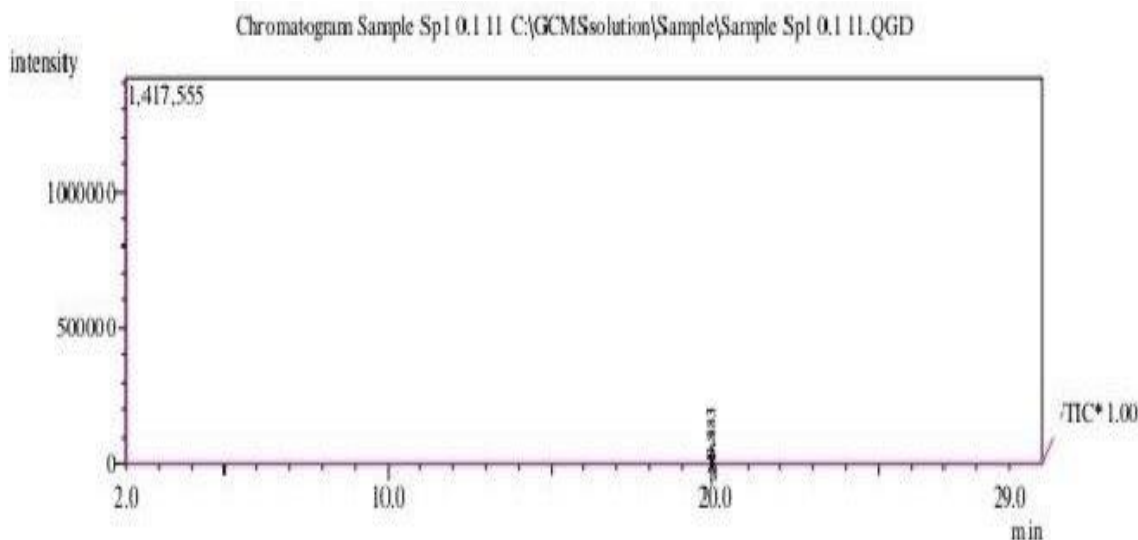


Fig. 6. Chromatogram (GC-MS) of soil samples contaminated with PAHs after 14 days of treatment with silver nanoparticles for extracts of willow leaves, chlorella algae, and spirulina, where the absence of the characteristic peaks for PAHs pollutants appears.

confirmed that green nanotechnology ensures achieving “zero pollutants” when the reaction is given a sufficient incubation period to overcome the obstacles of the structural complexity of organic materials.

CONCLUSION

The results indicated the efficiency of the green synthesis process of silver nanoparticles (AgNPs) using spirulina algae (*Spirulina platensis*) extract. Structural characterization results (UV-Vis, With the appearance of a surface plasmon resonance (SPR) band at a wavelength of 417 nm. The results of bioremediation also showed high efficiency of nano-silver spirulina treatments in removing PAHs (Anthracene, Fluoranthene, Chrysene) from artificially polluted soils. The results showed a direct relationship between the removal rates and the concentration of nanoparticles, as the concentration of 0.1 mg/L gave the highest removal rate of pollutant compounds during a period of 7 days compared to the concentrations of 0.01 and 0.001 mg/L. The results of the analysis of the polluted soil using GC-MS after 14 days of treatment showed the disappearance of all absorption peaks for the pollutants, and the recording of complete removal rates (100%) was achieved, which means decomposition. Pollutants completely or converted into simple intermediate products below the detection limit for compounds. This study indicated that the use of silver nanoparticles prepared using green methods from spirulina algae extract is an effective, innovative and economical solution, in addition to being eco-friendly, to address the problem of soil pollution with PAHs and reclaim contaminated soil.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

REFERENCES

1. Abdel-Shafy HI, Mansour MSM. A review on polycyclic aromatic hydrocarbons: Source, environmental impact, effect on human health and remediation. *Egyptian Journal of Petroleum*. 2016;25(1):107-123.
2. Eldos HI, Zouari N, Saeed S, Al-Ghouti MA. Recent advances in the treatment of PAHs in the environment: Application of nanomaterial-based technologies. *Arabian Journal of Chemistry*. 2022;15(7):103918.
3. Gupta N, Koley A, Banerjee S, Ghosh A, Hoque RR, Balachandran S. Nanomaterial-mediated strategies for enhancing bioremediation of polycyclic aromatic hydrocarbons: A systematic review. *Hybrid Advances*. 2024;7:100315.
4. Dutta V, Devasia J, Chauhan A, M J, L VV, Jha A, et al. Photocatalytic nanomaterials: Applications for remediation of toxic polycyclic aromatic hydrocarbons and green management. *Chemical Engineering Journal Advances*. 2022;11:100353.
5. Mazarji M, Minkina T, Sushkova S, Mandzhieva S, Bidhendi GN, Barakhov A, et al. Effect of nanomaterials on remediation of polycyclic aromatic hydrocarbons-contaminated soils: A review. *J Environ Manage*. 2021;284:112023.
6. Krishna SBN, Sheik AG, Pillay K, Ahmed Hamza M, Mohammed Elamir MY, Selim S. Nanotechnology in action: silver nanoparticles for improved eco-friendly remediation. *PeerJ*. 2024;12:e18191.
7. Dutta D, Das BM. Scope of green nanotechnology towards amalgamation of green chemistry for cleaner environment: A review on synthesis and applications of green nanoparticles. *Environmental Nanotechnology, Monitoring and Management*. 2021;15:100418.
8. Eker F, Akdaşçi E, Duman H, Bechelany M, Karav S. Green Synthesis of Silver Nanoparticles Using Plant Extracts: A Comprehensive Review of Physicochemical Properties and Multifunctional Applications. *Int J Mol Sci*. 2025;26(13):6222.
9. Ikhumetse AA, Abioye PO, Oyewole OA, Kovo AS, Josiah Ijah UJ. Biosynthesis of *Pseudomonas aeruginosa* mediated silver nanoparticles for remediation of crude oil contaminated water. *RSC Advances*. 2026;16(2):1212-1239.
10. Guda MA, Tsear AA, Saheb L. study of Using a Phyto-nanosynthesis of Silver and *Portulaca Oleracea* Plant Extracts in Petroleum Spots Treatment. *Journal of Petroleum Research and Studies*. 2024;14(2):138-149.
11. Li H, Liu L, Li C, Liu X, Ziadi N, Shi Y. Efficiency of Different Soil Sterilization Approaches and Their Effects on Soil Particle Size Distribution. *Journal of Soil Science and Plant Nutrition*. 2023;23(3):3979-3990.
12. Ubani O, Genevieve Onyinye O, Uba BO, Dokubo CU, Chinenye Azuka M, Akaun IP. Kinetic modelling and half-life study on bioremediation of diesel oil contaminated soil and water using nano remediation strategy. *Multidisciplinary Science Journal*. 2024;7(5):2025182.
13. Alcántara MT, Gómez J, Pazos M, Sanromán MA. PAHs soil decontamination in two steps: Desorption and electrochemical treatment. *J Hazard Mater*. 2009;166(1):462-468.
14. El-Shemy HA, Aboul-Enein AM, Aboul-Enein KM, Fujita K. Willow Leaves' Extracts Contain Anti-Tumor Agents Effective against Three Cell Types. *PLoS One*. 2007;2(1):e178.
15. Akdaşçi E, Eker F, Duman H, Bechelany M, Karav S. Microbial-Based Green Synthesis of Silver Nanoparticles: A Comparative Review of Bacteria- and Fungi-Mediated Approaches. *Int J Mol Sci*. 2025;26(20):10163.
16. Indhu AR, Minakshi M, Sivasubramanian R, Dharmalingam G. A Focus on Thermal Durability and Oxidation Resistance and Morphology of Polymer Capped Copper Particles Through a Synthesis-Driven, Precursor-Influenced Approach. *Nanomaterials*. 2025;15(24):1852.
17. Bayou S, Moujahid CE, Farissi HE, Roman C, Cacciola F, Chafik T. Stability and thermophysical properties of PAO-Based nanofluids with MWCNTs, nano-MoS₂ and their hybrid formulations for thermal applications. *Chem Eng Sci*. 2026;320:122585.

18. Synthesis of Silver Nanoparticles via Pulsed-Laser Ablation in Deionized Water: Characterization and Antibacterial Applications. *Nanosistemi, Nanomateriali, Nanotehnologii*. 2024;22(3).
19. Sivalingam AM, Pandian A, Kedari GSR, Kumar V. Identification of Bio-Active Compounds and Biochemical Characterization of Green Synthesized of Silver Nanoparticles (AgNPs) against Selected Uropathogenic Antimicrobial Activity. *Journal of Inorganic and Organometallic Polymers and Materials*. 2024;35(4):2904-2920.
20. Sandulovici RC, Carmen-Marinela M, Grigoriu A, Moldovan CA, Savin M, Ordeanu V, et al. The Physicochemical and Antimicrobial Properties of Silver/Gold Nanoparticles Obtained by "Green Synthesis" from Willow Bark and Their Formulations as Potential Innovative Pharmaceutical Substances. *Pharmaceuticals*. 2022;16(1):48.
21. Roy N, Gaur A, Jain A, Bhattacharya S, Rani V. Green synthesis of silver nanoparticles: An approach to overcome toxicity. *Environmental Toxicology and Pharmacology*. 2013;36(3):807-812.
22. Rastgar M, Ghasemi Z, Samari F. Biosynthesis of magnetic ZnO@Fe₂O₃ nanocomposites decorated with Ag/AgCl using Hormoz Island's red soil and Avicennia marina leaf extract. *Sci Rep*. 2025;15(1).
23. Chakravarty P, Deka H, Chowdhury D. Anthracene removal potential of green synthesized titanium dioxide nanoparticles (TiO₂-NPs) and *Alcaligenes faecalis* HP8 from contaminated soil. *Chemosphere*. 2023;321:138102.
24. Abbas S, Nasreen S, Haroon A, Ashraf MA. Synthesis of Silver and Copper Nanoparticles from Plants and Application as Adsorbents for Naphthalene decontamination. *Saudi J Biol Sci*. 2020;27(4):1016-1023.
25. Rajput VD, Kumari S, Minkina T, Sushkova S, Mandzhieva S. Nano-Enhanced Microbial Remediation of PAHs Contaminated Soil. *Air, Soil and Water Research*. 2023;16.
26. Fahim M, Shahzaib A, Nishat N, Jahan A, Bhat TA, Inam A. Green synthesis of silver nanoparticles: A comprehensive review of methods, influencing factors, and applications. *JCIS Open*. 2024;16:100125.
27. Gupta N, Banerjee S, Koley A, Bharali P, GhoshThakur R, Hoque RR, et al. Strategies for remediation of polycyclic aromatic hydrocarbons in contaminated soil: A systematic review and bibliometric analysis. *Applied Soil Ecology*. 2024;204:105688.
28. Siddiqui MN, Gondal MA. Nanocatalyst support of laser-induced photocatalytic degradation of MTBE. *Journal of Environmental Science and Health, Part A*. 2013;49(1):52-58.
29. Sun P, Bai J, Lian J, Tan Y, Chen X. Single and Combined Effects of Phenanthrene and Silver Nanoparticles on Denitrification Processes in Coastal Marine Sediments. *Microorganisms*. 2024;12(4):745.