

RESEARCH PAPER

Magnetic Fe₃O₄ Nanoparticles for the Removal of Petroleum Hydrocarbons and Polycyclic Aromatic Hydrocarbons from Tap Water

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ABSTRACT

This study investigated the total petroleum hydrocarbons (TPHs) and polycyclic aromatic hydrocarbons (PAHs) sources and levels in tap water samples in Amara city. Water samples collected from seven different sampling sites namely (Awasha, Al-Hussein, Al-jwadeen, Section 2, Al-Kaahraa, Al-Zahraa and Nahawind) during November 2024. Findings obtained from the present investigation showed the levels of (TPHs) fluctuated from 15.82 to 24.41 µg /l in Al-jwadeen and Nahawind respectively, whereas Σ16PAHs from 2622.77 to 17608.65 ng/l in Al-Kaahraa and Al-Hussein respectively. Also results of our study indicated that HPAHs were the most dominance pollutants in tap water compared with LPAHs in all sites. Fe₃O₄ nanoparticles were applied as a magnetic nanomaterial for reducing petroleum-related contaminants in the examined water samples. The prepared nanoparticles were characterized by XRD, FTIR, TEM and VSM before their use in the treatment experiments. Exposure of the water samples to Fe₃O₄ nanoparticles resulted in a measurable decrease in both TPHs and PAHs. TPH removal efficiencies ranged from 34.6% to 49.5%, while the reduction of Σ16PAHs ranged from 27.5% to 44.6% among the investigated sites. The average removal efficiencies of LPAHs and HPAHs were approximately 30.6% and 39.0%, respectively. These findings indicate that Fe₃O₄ nanoparticles have potential as a magnetically recoverable material for decreasing petroleum hydrocarbon contamination in tap water, although the degree of removal varied according to the sampling location and hydrocarbon fraction.

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INTRODUCTION

The field of nanotechnology has been continuously examined for the possibility of detecting and removing environmental contaminants, suitable nanoscale materials retain a large surface and possess suitable physiochemical characteristics that enable it to carry out this function. Iron-oxide nanoparticles

have recently emerged as a focal point of nanotechnology research on account of their surface reactivity and ease of recovery after use. The role of Iron-oxide based nanomaterials has already been investigated in various biological and applied chemical systems, which demonstrates their promising versatility as functioning nanoscale materials. Superparamagnetic iron

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oxide nanoparticles (SPION), offer the additional advantage of rapid separation by an external magnetic field, which may reduce the need for complicated recovery procedures after treatment [3,4]. These characteristics suggest that Fe_3O_4 nanoparticles may also have potential for the treatment of water contaminated with petroleum-derived compounds. Their use as a magnetically recoverable adsorbent could provide a simple approach for reducing TPHs and PAHs while allowing the nanoparticles to be separated from the treated water after contact.

Environmental pollutants can produce adverse effects in different biological systems, and their accumulation in air, soil and water remains an important ecological and public-health concern [5]. Hydrocarbon compounds are global pollutants of high importance due to their known adverse impacts on human health and widespread present in the ecosystems from both anthropogenic and natural sources [6]. PAHs are persistence carbon based pollutants distinguished by their molecular structures, which contain at least two interconnected aromatic rings sharing adjacent carbon atoms arranged in different constructions [7]. The main origins of these compounds include accidental petroleum, domestic wastes, industrial effluents, agricultural runoff, incomplete combustion of coal, plastics and tobacco, atmospheric releases associated with electricity-generating facilities and coal extraction operations and also from human activities related to the petroleum industry [8]. They also accumulate in living organisms and responsible for various negative affects including carcinogenicity, toxicity, mutagenicity, neurological disorders, immunological disorders, oxidative stress, reproductive inhibition, cardiovascular diseases and changes in normal behavior [9].

In resent time, PAHs have attracted global attention, sixteen PAHs are classified as main pollutants according to United States, Environmental Protection Agency U.S.EPA [10]. PAHs are accumulated in aquatic biota and posing threats to humans through skin contact, ingestion and inhalation but, the riskiness of these pollutants depends on their concentrations, the specific toxicity and exposure duration [11,12]. The PAHs with relatively low molecular masses (LPAHs) are more water soluble than high molecular weight (HPAHs), less lipophilic and more volatile compared with HPAHs. HPAHs are classified as

probable human carcinogens pollutants [13]. Their toxicity is dependent on the chemical structure, concentrations, the route of exposure and duration [14]. The primary objective of this investigation was to assessment levels of total petroleum hydrocarbon (TPH) concentrations and the levels of 16 individual polycyclic aromatic hydrocarbons (PAHs) in drinking water collected from Amara city to assess their risks on human health through and evaluated the findings against globally established regulatory limits for acceptable concentrations limits these pollutants.

MATERIALS AND METHODS

Collection of samples

Tap water samples were collected from seven different sampling sites namely (Awasha, Al-Hussein Quarter, Al-jwadeen Quarter, Section 28, Al-Kaahraa Quarter, Al-Zahraa Quarter and Nahawind) in dark glass bottles (their capacity 5 liter) from Amara city during November 2024. At every designated sampling location site, before sample collection, the container was thoroughly washed using water from the corresponding sampling location and then labeled. Water sample was stored in ice box to minimize the risk of potential microbial contamination degradation of PAHs or their photochemical degradation induced using Ultra Violate emissions before reaching the laboratory for subsequent analytical examination.

Fe_3O_4 nanoparticles

Fe_3O_4 nanoparticles were fabricated using co-precipitation method with minor modifications. Magnetic nanoparticles of Fe_3O_4 were prepared though a controlled chemical co-precipitation method, and its synthesis began by dissolving (0.005 mol) of ferric chloride and (0.0025 mol) of ferrous chloride in 50mL of deionized water. This preparation successfully established a $\text{Fe}^{3+}/\text{Fe}^{2+}$ molar ratio of 2:1. Additionally, 20mL of sodium hydroxide was combined with trisodium citrate in a separate 100mL three-necked reaction. The trisodium citrate was incorporated as a surface-stabilizing agent to strengthen electromagnetic repulsion between the particles and reduce their tendency to aggregate [16, 17].

Iron precursors was subsequently introduced dropwise into the alkaline citrate solution in the aqueous mixture while maintaining forceful mechanical stirring at 1500 rpm. Throughout the synthesis process, the reaction temperature

remained steady at 80°C under a nitrogen atmosphere to minimize unwanted oxidation. Stirring continued for 60 minutes to facilitate the formation of nanoparticles. A visual indication of magnetite precipitation was provided by a rapid transition of suspension from orange to deep black.

The resulting nanoparticles were isolated from the liquid phase using a permanent external magnet. Repeated washing of the collected particles was undertaken with deionized water and ethanol to eliminate residual salts and soluble impurities. Upon completion of the reaction, the synthesized Fe_3O_4 nanoparticles were subjected to a number of additional characterization techniques.

X-ray diffraction (XRD) was employed to investigate their crystalline structure, Fourier-transform infrared spectroscopy (FTIR) to identify characteristic chemical bonds and surface functional groups, transmission electron microscopy (TEM) to assess particle morphology and size, and vibrating sample magnetometry (VSM) to determine their magnetic behavior to confirm their structural, morphological and magnetic properties before use.

Treatment of water samples with Fe_3O_4 nanoparticles

Before hydrocarbon extraction, each water sample was divided into two portions. The first portion was kept untreated and used to determine the original concentrations of TPHs and PAHs. The second portion was treated with Fe_3O_4 nanoparticles. Fe_3O_4 nanoparticles was added to water samples at different concentrations at room temperature. After treatment, the nanoparticles were separated from the water. The resulting clear water was collected and subjected to the same extraction and analytical procedures applied to the untreated samples.

Extraction of hydrocarbon compounds from water samples

Hydrocarbon compounds were extracted from both untreated and Fe_3O_4 -treated tap-water samples. Petroleum hydrocarbons were isolated from tap water samples following the procedure outlined by UNEP (1989) [18]. Initially, 5 L of each water sample was combined with 50 mL of carbon tetrachloride (CCl_4) and subjected to continuous mechanical mixing for 30 min to facilitate the

transfer of hydrocarbons into the organic solvent. After mixing, the aqueous phase was removed, and the remaining solvent-containing fraction was introduced into a separatory funnel. The recovered organic phase was subsequently passed through a glass column packed with 5 g of anhydrous sodium sulfate (Na_2SO_4) to eliminate residual moisture. Using a rotary evaporator, the resulting extract was collected and concentrated to the point of dryness.

The dried residue was restored by placing it in a 50mL of n-hexane and applying it to a chromatographic glass column containing successive layers of glass wool at the base. At the uppermost layer, 15g of silica gel (100-200 mesh), 15g of alumina (100-200 mesh), and 10g of anhydrous sodium sulfate were placed. The hydrocarbon components were separated through sequential solvent elution. The aliphatic hydrocarbon fraction was first recovered using n-hexane as the mobile phase, followed by the collection of the aromatic hydrocarbon fraction using benzene. Both fractions were subsequently concentrated to dryness and preserved under appropriate storage conditions until instrumental analysis.

Note: The procedure retains the original experimental quantities and conditions. However, the analytical method should specify the storage temperature and instrumental detection technique to ensure reproducibility. The levels of PAHs individuals with HPLC apparatus type Shimadzo, whereas levels of TPHs was estimated by using Spectrofluorometer.

Calculation of removal efficiency

The removal efficiency of Fe_3O_4 nanoparticles was determined by comparing hydrocarbon concentrations before and after nanoparticle treatment using the following equation:

$$\text{Removal efficiency(\%)} = [(C_o - C_t) / C_o] \times 100$$

where (C_o) represents the concentration of the pollutant before treatment and (C_t) represents the concentration remaining after treatment. Removal efficiency was calculated for TPHs, total PAHs, individual PAH compounds, LPAHs and HPAHs.

RESULTS AND DISCUSSION

TPHs in tap water samples

The findings obtained from the current research

revealed levels of total petroleum hydrocarbon (TPH) concentrations, expressed in micrograms per liter ($\mu\text{g/L}$) in tap water samples in Amara City was 16.82, 17.63, 15.82, 23.64, 18.77, 21.29 and 24.41 in sites Awasha, Al-Hussein Quarter, Al-jwadeen Quarter, Section 28, Al-Kaahraa Quarter, Al-Zahraa Quarter and Nahawind respectively as shown in Fig. 1. Major sources as potential contributors to the occurrence of TPHs in sites studied come as of contamination the raw aquatic environments without proper treatment to remove these pollutants or mixing of domestic wastewater with drinking water due to breaks in the pipelines [19,20]. As well as biogenic sources

such as algae growth in pipelines, which produced certain hydrocarbon constituents and contributed to their release into the surrounding water [21].

PAHs in tap water samples

As showed in Table 1 and Fig. 2, the total concentration of 16 PAHs in the tap water samples varied between 2622.77 and 17608.65 ng/l in Al-Kaahraa Quarter and Al-Hussein Quarter respectively. the occurrence of polycyclic aromatic hydrocarbon (PAH) pollutants in tap water return to the application of coating materials containing hydrocarbons on pipes used for drinking water distribution some mineral-

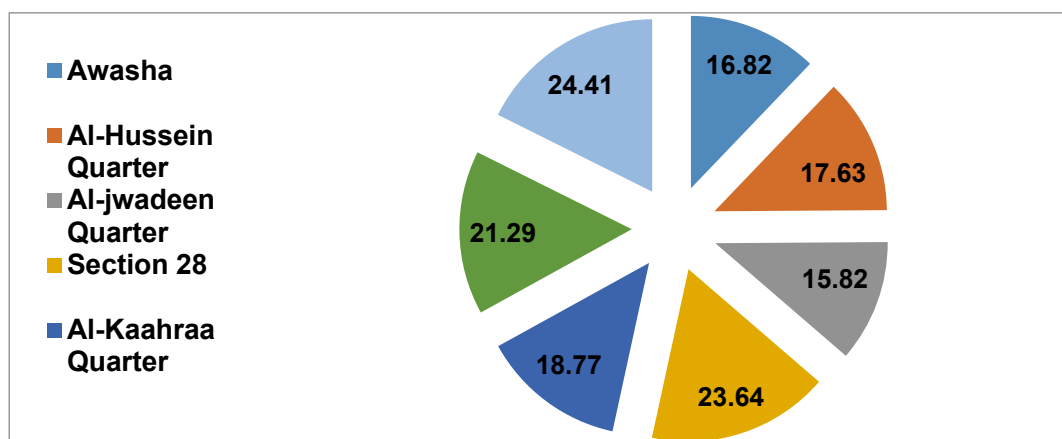


Fig. 1. Levels of TPHs ($\mu\text{g/l}$) in tap water samples.

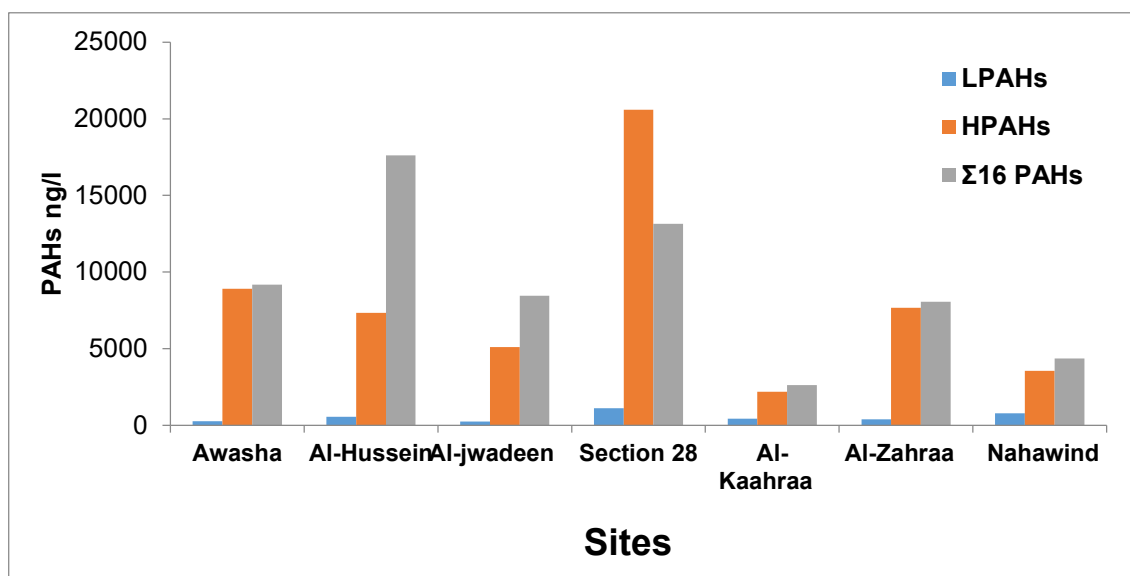


Fig. 2. Values of LPAHs, HPAHs and total PAHs in water samples.

based substances employed to provide reliable resistance to corrosive deterioration, in addition to that anaerobic condition and water disinfection by using chlorine remobilized PAHs from these matters [19,22]. The findings obtained from this investigation demonstrated that HPAHs were most

dominance pollutants in tap water compared with LPAHs in all sites (Fig. 2), due to their relatively high vapor and significant water solubility [21,23]. Also, the higher levels of HPAHs, could attributed because of their strong affinity for suspended particulate matter, which facilitates their retention

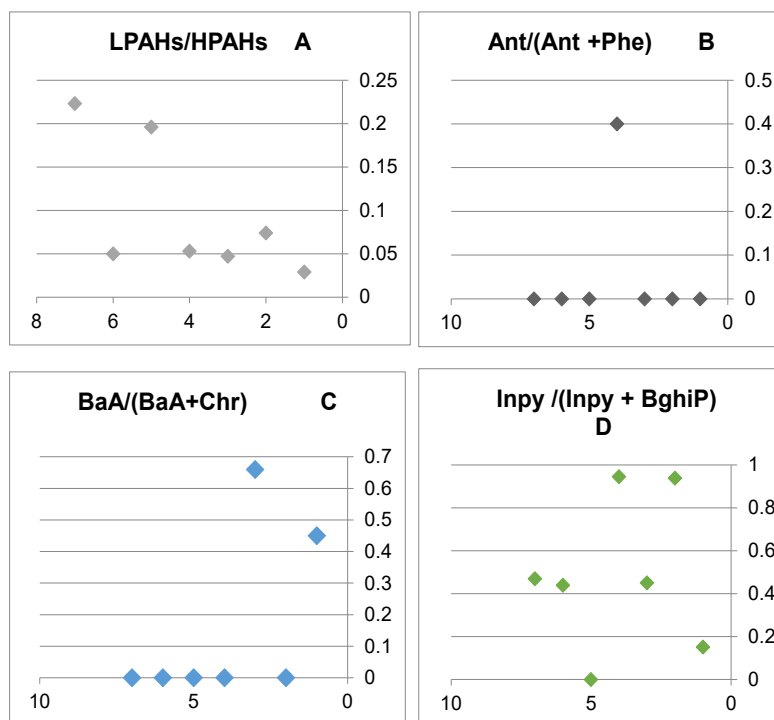


Fig. 3. Diagnostic ratios for origin identification of PAHs.

Table 1. Concentrations of polycyclic aromatic hydrocarbons (PAHs) in collected tap water samples, expressed in ng/L.

Name of components	The sites						
	Awasha	Al-Hussein	Al-jwadeen	Section 28	Al-Kaahraa	Al-Zahraa	Nahawind
Naphtalene	56.65	nd	nd	nd	18.76	nd	69.90
Acenaphthylene	nd	77.69	14.33	65.78	nd	68.96	nd
Acenaphthene	48.82	85.42	nd	87.52	nd	81.90	79.83
Fluorene	67.59	nd	226.31	nd	328.74	nd	643.90
Phenanthrene	91.86	nd	nd	569.37	nd	238.82	nd
Anthracene	nd	382.58	nd	387.24	83.63	nd	nd
Fluoranthene	983.39	nd	481.38	nd	nd	596.04	77.84
Pyrene	nd	547.83	nd	59.83	839.04	nd	nd
Benzo[a]anthracene	632.73	nd	266.82	nd	nd	3487.95	746.91
Chrysene	769.37	967.53	137.241	987.52	64.04	nd	nd
Benzo[b]fluoranthene	nd	561.58	nd	788.04	nd	237.83	nd
Benzo[k]fluoranthene	nd	nd	368.5	24.72	631.06	nd	432.72
Benzo[a]pyrene	47.37	nd	87.72	nd	nd	nd	623.96
Dibenzo[a,h]anthracene	nd	4627.8	nd	9687.02	657.50	1596.5	nd
Benzo[g,h,i]perylene	5491.74	625.88	3767.7	486.83	nd	986.07	886.93
Indeno[1,2,3-c,d]pyrene	983.62	9732.34	3098.3	8564.06	nd	773.72	788.84
Σ16 PAHs	9173.14	17608.65	8448.301	13143.87	2622.77	8067.79	4350.83

* nd = not detected

and prolonged persistence in aquatic systems. Despite the limited aqueous solubility of high-molecular-weight PAHs (HPAHs), their tendency to bind to suspended particles may enhance their transport, accumulation, and environmental persistence pollution [24]. The dominant HPAHs agreement which is consistent with the results reported in an earlier investigation examining the quality of drinking water in Misan, Iraq [20] and in Tehran, Iran [19].

Identification of PAHs origins

The potential sources contributing to the occurrence of PAHs in tap water samples depending through the application of the following diagnostic ratios. The LPAHs/HPAHs were employed to differentiate among pyrogenic less than one value and petrogenic larger than one value. LPAHs/HPAHs were less than one in all water samples (Fig. 3a). The present findings indicate origin of PAHs in tap water samples was pyrogenic and this could be associated with the activities of several oil companies operating in the area or release of fuels from motor boats [25]. Every collected water specimen revealed Ant / Ant plus Phe less than 0.1 (Fig. 3b), indicating that polycyclic aromatic hydrocarbons

(PAHs) are primarily generated through thermal decomposition and combustion-related processes from incomplete the burning of petroleum-based and other combustible fuels or from wood burning [24]. values for BaA / BaA with Chy exceeded the threshold value of 0.35 in two sites [24] (Fig. 3c) indicates pyrogenic origin whereas the ratio less than 0.20 indicates petroleum origin. The Inpy/ (Inpy + BghiP) diagnostic ratios exceeded 0.20 in water samples collected from every investigated location except in two sites (Awasha and Al-Kaahraa) (Fig. 3d) indicated sources of PAHs could be traced to thermal decomposition and combustion-related sources, as well as pyrogenic [26,27]. Depending on the diagnostic based on the PAH diagnostic ratios, contamination across the investigated locations was associated with both pyrogenic inputs, arising from the combustion of biomass, coal, wood, and fuels, and petrogenic contributions linked to petroleum-derived materials, including gasoline spills from boats, municipal sewers and industrial wastes.

Characterization of Fe_3O_4 nanostructures

Using X-ray powder diffraction (XRD), the crystalline characteristics of Fe_3O_4 nanoparticles were examined as illustrated in Fig. 4a and the

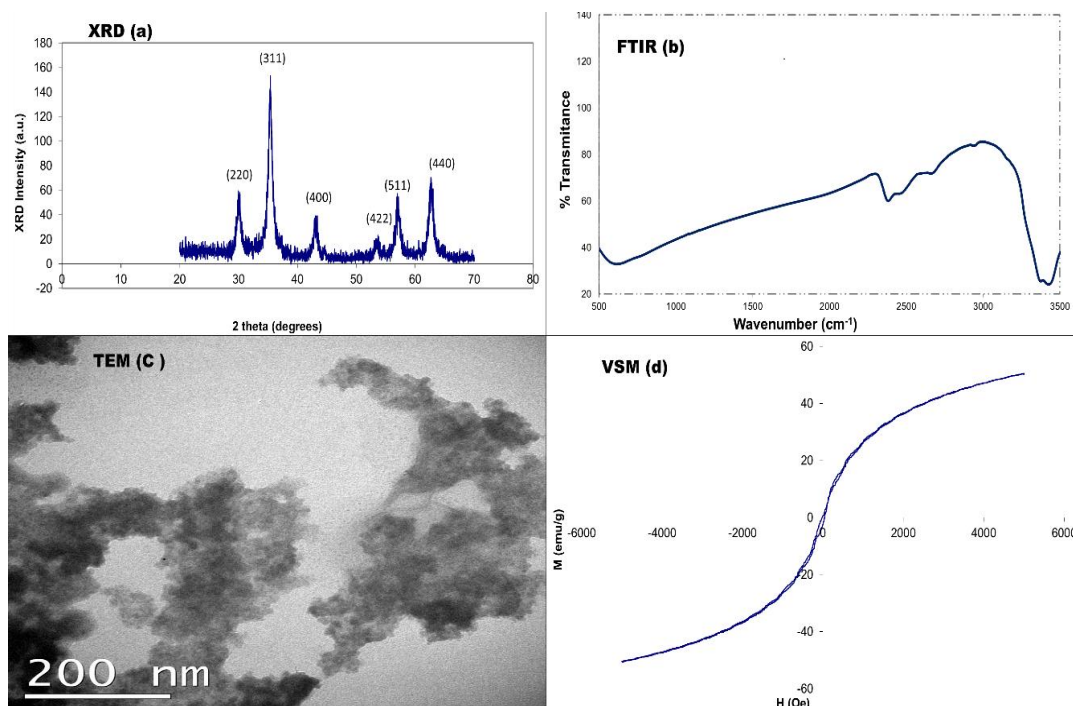


Fig. 4. Fe_3O_4 nanoparticles characterizations: (a) XRD, (b) FTIR. (c) TEM and (d) VSM.

recorded diffraction exhibited several distinct reflections that correspond to the crystallographic planes 220, 311, 400, 422, 511, and 440. These reflections closely matched the standard diffraction data for magnetite (JCPDS card No. 19-629) and supported the formation of Fe_3O_4 with a cubic inverse structure.

The chemical structure of the surface of the synthesized nanoparticles were further examined by Fourier-transform infrared (FTIR) spectroscopy. Evidence of the magnetite structure is provided by a prominent absorption peak appearing at 579 cm^{-1} which was assigned to the characteristic Fe-O stretching vibration [28]. The broad absorption region extending from 3600 to 3600 to 3300 cm^{-1} was attributed to O-H stretching vibration.

Transmission electron microscopy (TEM) was used to examine the morphology and particle size distribution of the resulting nanomaterials. The nanoparticles exhibited a relatively uniform appearance with an average diameter of approximately 20 nm and a narrow size distribution, as presented in Fig. 4c. These morphological observations were consistent with the formation of magnetite nanoparticles possessing a cubic crystalline phase.

The magnetic response of the synthesized Fe_3O_4 nanoparticles was evaluated at room temperature using vibrating sample magnetometry (VSM), with the corresponding magnetization curve presented in Fig. 4d. The magnetic measurements revealed negligible remanent magnetization and coercivity, accompanied by the absence of an appreciable hysteresis loop. Such behavior is characteristic of superparamagnetic nanoparticles [29,30] and can be associated with their sufficiently small dimensions and single-domain magnetic behavior [31]. Furthermore, the uncoated Fe_3O_4 nanoparticles attained a relatively high magnetization of 67 emu/g under an applied magnetic field of 15 kOe. Their average particle

diameter remained approximately 20 nm, with limited variation in particle size.

Removal of petroleum hydrocarbons by Fe_3O_4 nanoparticles

Treatment of the tap-water samples with Fe_3O_4 nanoparticles decreased the concentrations of petroleum hydrocarbons at all investigated locations. The extent of reduction varied among sites and between TPHs and PAHs. In general, the nanoparticles produced partial removal of the detected hydrocarbons, while measurable residual concentrations remained in the water after treatment.

Removal of TPHs by Fe_3O_4 nanoparticles

A decrease in TPH concentration was observed in all samples following treatment with Fe_3O_4 nanoparticles. Removal efficiencies ranged from 34.6% to 49.5%, with an average efficiency of 41.7%. The lowest removal was recorded in Al-jwadeen, where the TPH concentration decreased from 15.82 to 10.35 $\mu\text{g/L}$, corresponding to a removal efficiency of 34.6%. The greatest reduction was observed in Nahawind, where the concentration declined from 24.41 to 12.33 $\mu\text{g/L}$, representing 49.5% removal (as shown in Table 2).

These results indicate that Fe_3O_4 nanoparticles were capable of lowering the TPH burden in the examined tap water, although the magnitude of the response differed among sampling locations [32].

Removal of PAHs by Fe_3O_4 nanoparticles

Removal efficiency ranged from 27.5% to 44.6%, with a mean value of 36.6% across the seven sampling locations. Al-Hussein, which contained the highest initial $\Sigma 16\text{PAH}$ concentration, showed the greatest percentage reduction. The concentration decreased from 17608.65 to 9755.19 ng/L, corresponding to 44.6% removal.

Table 2. TPH concentrations in tap-water before and after treatment with Fe_3O_4 nanoparticles.

Sampling site	Before treatment ($\mu\text{g/L}$)	After treatment ($\mu\text{g/L}$)	Removal efficiency (%)
Awasha	19.36	11.36	41.3
Al-Hussein	22.74	12.10	46.8
Al-jwadeen	15.82	10.35	34.6
Section 28	18.91	11.52	39.1
Al-Kaahraa	17.65	11.17	36.7
Al-Zahraa	21.43	12.02	43.9
Nahawind	24.41	12.33	49.5
Mean	20.05	11.55	41.7

Table 3. Σ 16PAH concentrations before and after treatment with Fe₃O₄ nanoparticles.

Sampling site	Before treatment (ng/L)	After treatment (ng/L)	Removal efficiency (%)
Awasha	7956.42	5187.59	34.8
Al-Hussein	17608.65	9755.19	44.6
Al-jwadeen	6854.33	4736.34	30.9
Section 28	9321.58	5900.56	36.7
Al-Kaahraa	2622.77	1901.51	27.5
Al-Zahraa	11436.26	6884.63	39.8
Nahawind	13782.51	7980.07	42.1
Mean	9938.07	6050.84	36.6

Table 4. Changes in LPAH and HPAH concentrations following Fe₃O₄ nanoparticle treatment.

Sampling site	LPAHs before (ng/L)	LPAHs after (ng/L)	LPAHs removal (%)	HPAHs before (ng/L)	HPAHs after (ng/L)	HPAHs removal (%)
Awasha	2386.93	1682.78	29.5	5569.49	3504.80	37.1
Al-Hussein	4226.08	2789.21	34.0	13382.57	6965.98	47.9
Al-jwadeen	2261.93	1651.21	27.0	4592.40	3085.13	32.8
Section 28	2610.04	1795.71	31.2	6711.54	4104.85	38.8
Al-Kaahraa	917.97	697.66	24.0	1704.80	1203.85	29.4
Al-Zahraa	3087.79	2053.38	33.5	8348.47	4831.25	42.1
Nahawind	3445.63	2239.66	35.0	10336.88	5740.42	44.5
Mean	—	—	30.6	—	—	39.0
removal	—	—	30.6	—	—	39.0

Nahawind showed the second greatest response, with 42.1% of the initial PAH concentration removed. The smallest reduction was observed in Al-Kaahraa. Its Σ 16PAH concentration decreased from 2622.77 to 1901.51 ng/L, representing a removal efficiency of 27.5%. The remaining sites showed intermediate responses ranging from 30.9% to 39.8% (Table 3).

The reduction in Σ 16PAHs was therefore somewhat lower than that recorded for TPHs. However, the response was evident at every sampling location, demonstrating that PAHs present in the water were also affected by Fe₃O₄ treatment.

Removal of LPAHs and HPAHs

Differences were also observed when PAHs were separated into low- and high-molecular-weight groups. Before nanoparticle treatment, HPAHs represented the predominant fraction at all sampling locations, in agreement with the pattern observed in the original water samples. Both PAH groups decreased following treatment; however, HPAHs showed a generally greater proportional reduction than LPAHs. The mean removal of LPAHs among the investigated sites was approximately 30.6%, whereas HPAH removal averaged approximately 39.0%. The lowest LPAH removal was observed in Al-Kaahraa at 24.0%,

while the highest was recorded in Nahawind at 35.0%. HPAH removal ranged from 29.4% in Al-Kaahraa to 47.9% in Al-Hussein (Table 4).

Although HPAHs showed the greater proportional reduction, they remained the dominant PAH fraction after treatment because their initial concentrations were considerably higher than those of LPAHs. Fe₃O₄ nanoparticle treatment reduced TPHs, Σ 16PAHs, LPAHs and HPAHs in the investigated tap-water samples.

RPH removal rates ranged between 34.6% and 49.5% while Σ 16PAH rates ranged between 27.5% and 44.6%. The variation of this rate between different locations and PAH groups is a strong indicator that the response to Fe₃O₄ was contingent upon the response to Fe₃O₄ treatment was dependent on the composition of hydrocarbons present in each water sample.

CONCLUSION

The occurrence of Total Petroleum Hydrocarbons (TPHs) in the investigated locations are primarily associated with the introduction of contaminated raw water into drinking supply systems where conventional treatment processes are either non-existent or insufficient to eliminate petroleum-derived pollutants. The analytical findings further established that high-molecular weight polycyclic cycle aromatic hydrocarbons

(HPAHs) predominated over low-weight PAHs (LPAHs) in tap water collected from the different investigated sites. A reduction in TPH and Pah concentrated across the examined water supplies was achieved by application of Fe₃O₄ nanoparticles, though the extent of contaminant removal varied between different sampling locations and between LPAH and HPAH fractions. The magnetic responsiveness of Fe₃O₄ nanoparticles also offers a practical environment by allowing the particles to be recovered and possibly reused by an external magnetic field. These findings highlight the importance of preventing petroleum-related contaminants from entering drinking water at the source, and improving water monitoring and filtration programs to reduce human exposure to hazardous hydrocarbon compounds and safeguard drinking water quality.

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CONFLICT OF INTEREST

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

REFERENCES

1. Zainab JM, Sahira K, Al-Abboodi AK, Alsaady HA. Enhancing Pediculicidal Activity Against *Pediculus humanus capitis* Using Iron Oxide Nanoparticle-Based Formulations of some Plant Extracts and Acetic Acid Solution. *Nigerian Journal of Parasitology*. 2024;45(2):460-469.
2. Al-Abboodi A, Fahih IQ, Al-Asadi M, Hussein BA, Al-Saady MAAJ, Abdullah TA, et al. Iron-oxide nanoparticles (SPIONs) enhance malaria vaccine antibody response. *Vaccine*. 2026;77:128353.
3. Ramadan AK, Abd S, Abduljabbar Ridha Al-Ali Z, Al-Abboodi A. Enhanced Anti-Obesity Efficacy of Orlistat via Co-Administration with Iron Oxide Nanoparticles (SPIONs) in a High-Fat Diet-Induced Obese Mice Model. *Journal of Nanostructures*. 2026;16(1):995-1003.
4. Al-Abboodi Y, Ridha A, Fasullo M, Naguib MT. Risks of PEG tube placement in patients with cirrhosis-associated ascites. *Clin Exp Gastroenterol*. 2017;Volume 10:211-214.
5. Sofo A, Elshafie HS, Camele I. Structural and Functional Organization of the Root System: A Comparative Study on Five Plant Species. *Plants*. 2020;9(10):1338.
6. Fadare OO, Conkle JL, Siddiqui S, Brander SM. What Are Pollutants, Contaminants, and Chemicals of Emerging Concerns (CECs). *Aquatic Ecotoxicology*: Springer International Publishing; 2024. p. 11-19. http://dx.doi.org/10.1007/978-3-031-53130-9_2
7. Zhang X, Wang X, Zhao X, Tang Z, Liang W, Wu X, et al. Important But Overlooked Potential Risks of Substituted Polycyclic Aromatic Hydrocarbon: Looking Below the Tip of the Iceberg. *Rev Environ Contam Toxicol*. 2022;260(1).
8. Jindal S, Chaudhary Y, Aggarwal KK. Toxicity of polyaromatic hydrocarbons and their biodegradation in the environment. *Green Chemistry Approaches to Environmental Sustainability*: Elsevier; 2024. p. 43-66. <http://dx.doi.org/10.1016/b978-0-443-18959-3.00009-4>
9. José S, Jordao L. Exploring the Interaction between Microplastics, Polycyclic Aromatic Hydrocarbons and Biofilms in Freshwater. *Polycyclic Aromatic Compounds*. 2020;42(5):2210-2221.
10. Trakoli A. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans. Volume 99: Some Aromatic Amines, Organic Dyes, and Related Exposures. *International Agency for Research on Cancer. Occup Med*. 2012;62(3):232-232.
11. Mallah MA, Changxing L, Mallah MA, Noreen S, Liu Y, Saeed M, et al. Polycyclic aromatic hydrocarbon and its effects on human health: An overview. *Chemosphere*. 2022;296:133948.
12. Aziz ZS, Jazza SH, Dageem HN, Banoon SR, Balboul BA, Abdelzaher MA. Bacterial biodegradation of oil-contaminated soil for pollutant abatement contributing to achieve sustainable development goals: A comprehensive review. *Results in Engineering*. 2024;22:102083.
13. Khuman SN, Chakraborty P, Cincinelli A, Snow D, Kumar B. Polycyclic aromatic hydrocarbons in surface waters and riverine sediments of the Hooghly and Brahmaputra Rivers in the Eastern and Northeastern India. *Sci Total Environ*. 2018;636:751-760.
14. Rengarajan T, Rajendran P, Nandakumar N, Lokeshkumar B, Rajendran P, Nishigaki I. Exposure to polycyclic aromatic hydrocarbons with special focus on cancer. *Asian Pacific Journal of Tropical Biomedicine*. 2015;5(3):182-189.
15. He R, You X, Shao J, Gao F, Pan B, Cui D. Core/shell fluorescent magnetic silica-coated composite nanoparticles for bioconjugation. *Nanotechnology*. 2007;18(31):315601.
16. Liu X, Ma Z, Xing J, Liu H. Preparation and characterization of amino-silane modified superparamagnetic silica nanospheres. *J Magn Magn Mater*. 2004;270(1-2):1-6.
17. Liu X, Xing J, Guan Y, Shan G, Liu H. Synthesis of amino-silane modified superparamagnetic silica supports and their use for protein immobilization. *Colloids Surf Physicochem Eng Aspects*. 2004;238(1-3):127-131.
18. Wade TL, Driscoll SK, McGrath J, Coolbaugh T, Liu Z, Buskey EJ. Exposure methodologies for dissolved individual hydrocarbons, dissolved oil, water oil dispersions, water accommodated fraction and chemically enhanced water accommodated fraction of fresh and weathered oil. *Mar Pollut Bull*. 2022;184:114085.
19. Karyab H, Yunesian M, Nasser S, Mahvi AH, Ahmadkhaniha R, Rastkari N, et al. Polycyclic Aromatic Hydrocarbons in drinking water of Tehran, Iran. *Journal of Environmental Health Science and Engineering*. 2013;11(1).
20. Al-Saad HT, Jazza S. Quality Assessment of Drinking Water in Missan Province, Iraq. *International Journal of Marine Science*. 2016.
21. Hamid T A-S. Using Two Species From Common Aquatic Plants as Bio-indicators of Pollution With Hydrocarbons Compounds in Al-Kahlai River -Misan Province/ Iraq. *International Journal of Marine Science*. 2016.
22. Leptospira: background document for the WHO guidelines for drinking-water quality: World Health Organization; 2025
23. Hasan GMMA, Rinky F, Ahmed KS, Sikdar K, Moniruzzaman

- M. Assessment of polycyclic aromatic hydrocarbons (PAHs) and heavy metal contamination in Shitalakshya River water: ecological and health risk implications. *Environmental Monitoring and Assessment*. 2025;197(3).
24. Nwaozuzu CC, Abah SO, Patrick-Iwuanyanwu KC. Polycyclic aromatic hydrocarbon in community drinking water, Nsisioken, Nigeria: Source and health risk assessment. *Environmental Analysis Health and Toxicology*. 2024;39(2):e2024015.
25. WATER QUALITY ASSESSMENT IN THE AL-MUSAYYIB RIVER/ EUPHRATES SYSTEM USING THE RIVER POLLUTION INDEX (RPI). *European Chemical Bulletin*. 2022;11(5).
26. Adeniji AO, Okoh OO, Okoh AI. Distribution pattern and health risk assessment of polycyclic aromatic hydrocarbons in the water and sediment of Algoa Bay, South Africa. *Environmental Geochemistry and Health*. 2018;41(3):1303-1320.
27. Jazza SH, Al-Adhub AHY, Al-Saad HT. Polycyclic Aromatic Hydrocarbons (PAHs) in water of Al-Kahlai River in Missan Province, Iraq. *ILMU KELAUTAN: Indonesian Journal of Marine Sciences*. 2016;21(1):1.
28. Al-Abboodi A, Albukhaty S, Sulaiman GM, Al-Saady MAAJ, Jabir MS, Abomughaid MM. Protein Conjugated Superparamagnetic Iron Oxide Nanoparticles for Efficient Vaccine Delivery Systems. *Plasmonics*. 2023;19(1):379-388.
29. Priyadharshini P, Shobika PA, Monisha P, Gomathi SS, Pushpanathan K. Nickel ferrite magnetic nanoparticles: evidence for superparamagnetism in smaller size particles. *Journal of the Australian Ceramic Society*. 2022;58(5):1455-1480.
30. Singh N, Pritam A, Singh V, Katin K, Fransson J, Mondal PC. Turning Superparamagnetic Nanoparticles Into Ferromagnetic at Room Temperature via Molecular Functionalization for Magnetic Memory Applications. *Angew Chem Int Ed*. 2025;65(3).
31. de Menezes JR, Gomes LG, Fabris F, de Almeida AA, Tancredi P, Barbosa M, et al. Review: Determining effective magnetic anisotropy in magnetic nanoparticles systems using DC-magnetometry methods. *Journal of Materials Science*. 2026;61(41):31675-31706.
32. S SR, Sampath S, Samiappan SC. Nano-enabled phytoremediation of petroleum hydrocarbon-contaminated soils: mechanisms, experimental evidence, and future perspectives: a systematic review. *Environmental Geochemistry and Health*. 2026;48(8).