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Utilization of Mentha Extract for sustainable Iron Nanoparticles preparation to mitigating Heavy Metals Contamination from Drinking water: a study of Rawalpindi District, Pakistan

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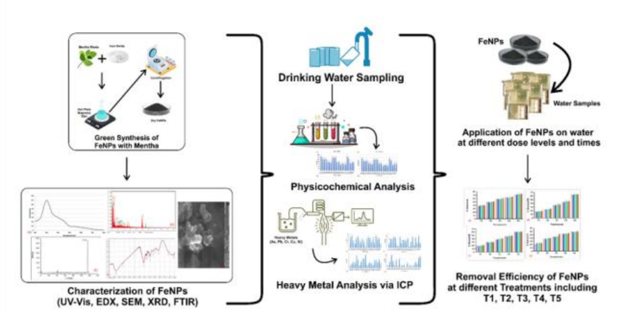
Graphical abstract



Abstract

The present study was conducted to examine the synthesis and utilization of *mentha*-mediated iron nanoparticles as an innovative adsorbent to remove heavy metals from water. Iron nanoparticles were synthesized by employing *menthe* extract as a reducing and stabilizing agent. The synthesized FeNPs were characterized by SEM for morphology, ultraviolet-visible spectroscopy for optical properties (UV), and Fourier-transform infrared spectroscopy (FTIR for functional groups, EDX for elemental composition, and XRD for structure and composition. The SEM images showed the defined nanoparticles exhibiting a consistent size distribution. The FTIR and UV analyses validated the effective formation of nanoparticles and identified functional groups that participated in the reduction process. Subsequently, synthesized nanoparticles were implemented as adsorbents to remove extract particular heavy metals from water at varying doses and times. The investigation of experimental samples was carried out by inductively coupled plasma optical emission spectrometry (ICP-OES) to measure the heavy metal concentrations in the water. The findings of the study indicated that iron nanoparticles mediated by *Mentha* were effective for removing concentration of heavy metals more than 60% of all the selected heavy metals in the water samples. This study contributes to the dynamic domain of water purification strategies propelled by nanotechnology. It highlights the potential of utilizing natural extracts, such as *mentha*, in environmentally friendly synthesis processes to remediate environmental issues. The results have potential implications for the advancement of environmentally friendly and efficient strategies to tackle the issue of water pollution.

Keywords: Adsorption, *Mentha*, Iron nanoparticles, Green synthesis, Heavy metals, Water pollution,

1. Introduction

Water pollution is now the most persistent issue facing the whole earth. The water is affected by various sources of pollution, such as chemical waste, microbial contamination, industrial waste and radioactive waste (Baloch *et al.* 2023). It has been observed that the quality of groundwater is deteriorating due to chemical, physical, and biological contaminants (Singh *et al.* 2017), where heavy metal play a crucial role in water toxicity (Sharma *et al.* 2025). The deteriorating water quality directly impacts all living beings; therefore, safe and clean drinking water is necessary for the survival of humans and life on earth. According to WHO, 80% of the diseases in the world are due to improper sanitation, polluted drinking water, and unavailability of clean water (Akbar *et al.* 2025). Furthermore, the UNICEFEF report documented that a mere 10% improvement in access to safe drinking water was observed globally and a 16% growth in the supply of safely managed sanitation systems over the period of 2000-2017 (Yeboah *et al.* 2022).

Heavy metals are one of the significant and important water pollutants. The severe use of heavy metals in the industry has increased the concentration of these metallic substances in natural water (Sandeep *et al.* 2019). Heavy metal ions in drinking water cause toxicity, harming human health and other organisms. These metals are increasing rapidly due to the increase in urban areas and their use in agricultural and other industrial sectors. In agriculture, the extensive use of pesticides and fertilizers is the leading cause of heavy metal contamination (Ndimele *et al.* 2013). Industrial pollutants usually comprise zinc, nickel, lead, copper, chromium, and cadmium, other metals and their oxides. The anthropogenic actions, such as the exaction of ingredients, silver-plating, insecticides, manufacturing, mining biosolids, fertilizer production, alloys manufacturing, and batteries production (Gabal *et al.* 2020) are a few examples of sources of heavy metals in water.

The current study was planned to address the important issue of contaminated drinking water used by the population. According to the report published by Pakistan Council of Research in Water Resources (PCRWR report 2021), on the status of drinking water quality in Pakistan. Two major reservoirs i.e Khanpur and Rawal Dams supplement water to both cities. Rawalpindi (33.5848° N, 73.0658° E), is the 4th largest densely populated city of Pakistan. As the twin cities of Pakistan's federal capital, Islamabad and Rawalpindi. Both cities have undergone rapid demographic growth accompanied by the expansion of industries such as textiles, metal processing, and pharmaceuticals. Report highlighted these activities as potential contributors to heavy metal release into the water resources. At the same time, most of the local population depends on groundwater pumped through tube wells or hand pumps as their primary source of drinking water, which increase the risk of exposure to contamination. Nevertheless, detailed investigations that systematically assess the concentrations of multiple heavy metals in the drinking water resources of Rawalpindi remain limited. Conventional water filtration plants are not only costly but also rely heavily on the addition of chemicals for purification, which may pose environmental and economic concerns. The health associated impacts of heavy metals, for instance, in the case of lead, anxiety problems, cancer, failure of renal, and anemia, are related to a large lead quantity in drinking water. Several other metals, including Hg, Cd, and Cr (Wu *et al.* 2020) are causing the greatest impact on community health, because of the toxicity of these metals, even at minor levels.

In order to remove these heavy metals from water there are various methods have been adopted. For example, adsorption, biosorption precipitation, electrochemical treatments, membrane filtration, evaporation, oxidation, flotation, and ion exchange are few example. Among these, adsorption is considered an efficient technique for hazardous metal ions from water (Wu *et al.* 2020). Various studies have been performed for the removal of heavy metals from water using nano-based adsorbents. The size of nanoparticles and their characteristics vary, as reported by many studies. Interestingly, the science of nanotechnology has remarkably improved and getting the attention of scientists all over the world (Mallikarjunaiah *et al.*2020). Nanomaterials have diverse geometric characteristics, such as large surface area and their specific surface charge, porosity ionic reactivity, and functionality, which can assist in the efficient removal of heavy metals (Patlolla *et al.* 2009).

The nanomaterials can be synthesized using different methods such as chemical, physical, and biological processes. Among these methods, green synthesis is an eco-friendly approach as it uses plant or fungal extracts to reduce metal salts to respective nanoparticles. Furthermore, these nanoparticles also have less toxicity to food chain systems (Deepa *et al.* 2020). Iron nanoparticles have been widely used for heavy metal removal from water due to their high surface area and reactivity, which enhances the adsorption and reduction capabilities. Moreover, their synthesis generates less secondary waste, unlike traditional methods such as chemical precipitation or ion exchange (Siddeeg *et al.* 2020). It has been reported that the *menthe* extract-based iron nanoparticles could have the ability to chelate heavy metals, therefore reducing the concentration of heavy metals in the drinking water. In the above context the goal of the present study the goal was to explore alternate green that can be potentially utilized to purify the water. In this study waste materials of *mentha* plant from local vegetable market was utilized for synthesize of iron nanoparticles, which were subsequently applied for the removal of heavy metals from drinking water.

2. Materials and methods

2.1. Study area and water sample collection

Water samples were collected from one of the major city of Punjab province i.e. Rawalpindi in Pakistan (**Figure 1**). Random sampling was performed from 21 sites and standardized criteria was followed for sample collection. It is also important to note that samples were collected at a distance of 4 km to make sure that representatives samples were collected from the whole location. The sampling locations were selected based on permanent public water sources, drinking public water outlets and houses.

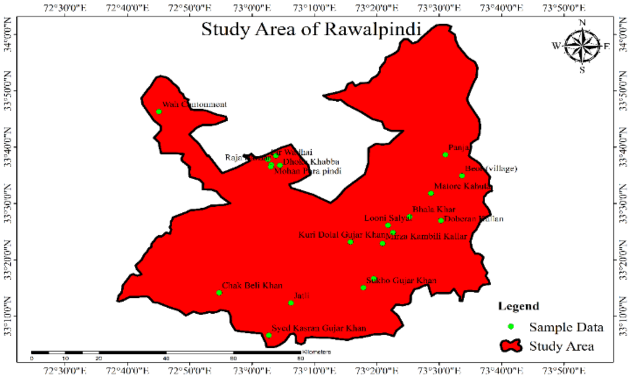


Figure 1. Detailed map showing study area and water sample collection sites of Rawalpindi Pakistan

2.1.1. Physico-Chemical Analysis of water samples

The physicochemical analysis includes pH, total dissolved solid (TDS), hardness, electrical conductivity (EC), and turbidity were performed using the reference methods of Pakistan Standards and Quality Control Authority (PSQCA 2004).

2.1.2. Heavy Metals Analysis by ICP-OES

The heavy metals present in the collected water samples were quantified utilizing inductively coupled plasma (ICP-OES 5110) in accordance with the methodology outlined in the standard publication (Ahmad *et al.* 2023). The ICP-OES equipped with an auto-sampler and a scanning CCD detector, was utilized to determine metal concentrations through a standard calibration method. Data acquisition and processing were conducted using the WinLab32ICP software. All analyses were carried out in compliance with the ISO standard for water quality determination.

2.2. Sampling of menthe plant

Fresh *mentha* leaves were obtained from the local vegetable market of Rawalpindi. The leaves were surface cleansed by flowing water and distilled water to remove the dust particles and other impurities. The cleaned leaves were subjected to drying at room temperature for few hours.

2.2.1. Preparation of menthe extracts

For the preparation of menthe extract 20 gm of leaves were placed in a 250 mL beaker containing 00 mL of double distilled water. The extract was boiled for 30-45 minutes on a continuous flam. The extract was cooled and filtered with Whatman paper filter no. 42. The final prepared extract was stored at ambient temperature for further use.

2.3. Synthesis of Fe NPs using menthe extract

For synthesis of Fe NPs 1 mM salt solution was prepared by mixing 0.43 g of ferric nitrate in 500 mL of double-distilled water. The solution was continuously stirred on a magnetic stirrer at 150 °C for five h, while *menthe* extract was added drop by drop. The synthesis of Fe NPs was confirmed by observing the transformation from colorless to brown after four days of incubation in the dark conditions. The solution was centrifuge for 20 min at 13000 rpm and the precipitates were separated and remove the supernatant, the particles obtained were rinsed with 10 mL of methanol. The precipices were washed several times with water and methanol alternatively and dried at at 40 °C in an oven.

2.3.1. Characterization of Mentha-Mediated Fe NPs:

The characterization of the synthesized Fe NPs was performed using various tools. UV-visible spectroscopy (UV-752pc spectrophotometer) was used to captured spectra and absorption at 200-800 nm (Verma *et al.* 2017). Scanning electron microscopy (SEM) was performed using JSM5910, JEOl, JAPAN equipment at an energy of 30 kV and a minimum and maximum magnification of 2.3 nm and 30,000x, respectively (Ahmad *et al.* 2024). Fourier transform infrared (FTIR) was used to determine functional groups in the phytomediated synthesized FeNPs. The FTIR spectrum of dried FeNP powder pelleted with potassium bromide was acquired as a wavenumber in the range of 500–4000 cm^{-1} using a Perkin-Elmer FTIR-Spectrum, Akron, OH, USA (Karunakaran *et al.* 2018).

2.4. Experimental setup for heavy metal removal with Fe NPs adsorbent

The treatment of drinking water was tested with selected heavy metals (As, Pb, Ni, Cr and Cu) solutions (synthetic wastewater) using Fe NPs assisted adsorption process. The Experiments were performed at five different interval of times (15 min, 30 min, 45 min, 60min, 75minutes) for the adsorption of heavy metals. There are five different doses of FeNPs were used determine the degree of reactivity shown by the FeNPs by adding in various dose ranging from 0.25mg/L – 1.25 mg/L in different treatments. During these experiments the concentration of heavy metals in the solution was constant at 5 mg/L. After that the stock solution of heavy metals contacted with the adsorbent, shake at specified time on the 120 rpm orbital shaker, separated by a piece of magnet, and centrifuged in the 5000 rpm. In the end of each experiment, the residual concentration of heavy metals in solution was determinate, according to standard method describe by (Ahmad *et al.* 2023).

2.5. Inductively Coupled Plasma Optical Emission Spectroscopy Analysis:

Inductively coupled plasma optical emission spectroscopy (ICP-OES) analysis of the filtrate performed to ascertain the concentration of residual heavy metals. Using the following formula, adsorption efficiency (%) was determined:

$$\text{Removal Efficiency} = (C0 - Cf\ /\ C0) \times 100$$

Where: The initial metal concentration is C0 (ppm)

The Final metal concentration after adsorption is Cf (ppm) (Ahmad *et al.* 2023).

3. Results

3.1. Physico-Chemical Analysis of Collected Water Samples

The physico-chemical analysis of water samples including pH, TDS, EC and Turbidity were performed for collected water samples from Rawalpindi, district of Punjab, Pakistan. The results are presented in the following section.

3.1.1. Variation in pH of collected samples

Statistical analysis shows that water samples from different areas of the district Rawalpindi have pH ranges from 6 to 8.6. The results show that RWP16 had a higher acidic pH (6.5) and sample RWP2 had a higher alkaline pH (8.6) (**Figure 2A**). The results show that the pH is within the limits of PSQCA standards except for a few that are slightly higher or lower than the recommended set value (i.e. 6.5 to 8.5). The data obtained from the present study were parallel with the findings of a previous investigation (Javed and Mashwan 2020), which reported the pH of water from Rawalpindi filtration plants in the range of 6.89 to 7.87, along with other physicochemical properties of drinking water.

3.1.2. Hardness

Current study results show that water samples from different areas of the district Rawalpindi range from 93 to 337 mg/L (**Figure 2B**). The results show that the maximum hardness value (337 mg/L) was found in RWP17, while the minimum value (93 mg/L) was recorded in sample RWP16. The results show that the hardness of water is within the limits of WHO standards. The data obtained from the present study was parallel with the finding of previous investigation by (Javed and Mashwan 2020), who find hardness of water from Rawalpindi filtration plants was in range of 140 mg/L to 515 mg/L.

3.1.3. Total Dissolved Solids

The total dissolved solids (TDS) of water samples collected from different areas of the district Rawalpindi range from 543 to 1275 mg/L (**Figure 2C**). The results show that the maximum TDS value (1275 mg/L) was found in RWP1, while the minimum value (543 mg/L) was recorded in sample RWP13. The data obtained from the present study has similarity with the finding of previous investigation by(Javed and Mashwan 2020), who reported TDS of water from Rawalpindi filtration plants with range of 163 mg/L to 884 mg/L along with other physicochemical properties of drinking water.

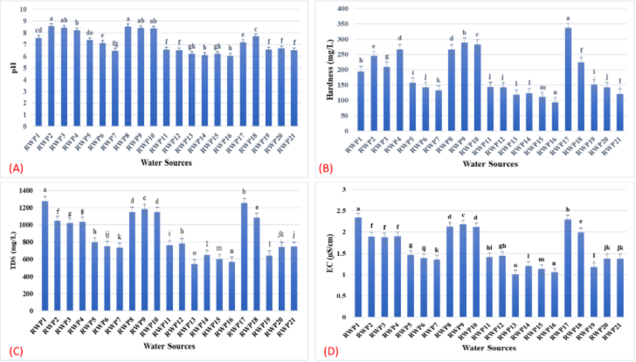


Figure 2. Physiochemical properties of water samples collected from different sources of Rawalpindi: (A) pH, (B) Hardness, (C) TDS, (D) EC

3.1.4. Electrical Conductivity

Statistical analysis shows that water samples from different areas of district Rawalpindi ranged from 1.01 to 2.34 mS/cm (**Figure 2D**). The results show that the maximum EC value (2.34 mS/cm) was found in RWP1, while the minimum value (1.0 mS/cm) was recorded in sample RWP13. The data obtained from the present study has similarity with the finding of previous investigation by (Javed and Mashwan 2020), who reported EC of water from Rawalpindi filtration plants with range of 296 µS/cm to 1474 µS/cm along with other physicochemical properties of drinking water.

3.1.5. Turbidity

The result regarding total turbidity of water samples has a range from 0.76 to 5.19 NTU collected from different areas of the district Rawalpindi. It is evident from the results that the maximum turbidity value (5.19 NTU) was found in RWP20, while the the minimum value (0.76 NTU) was recorded in sample RWP15. The results showed that turbidity is within the limits of PSQCA standards (i.e. ≤ 5 NTU). Only one sample was found above the set limit, which might be due to a polluted source in the the nearby area. The data obtained from the present study is similar to the findings of a a previous investigation by (Javed and Mashwan 2020), who reported turbidity of water within the limit of WHO/PSQCA.

3.2. Metal Analysis of Collected Water Samples from Rawalpindi

3.2.1. Arsenic (As)

The result regarding the presence of arsenic (As) in water samples collected from various regions of the Rawalpindi district have concentrations ranging from 0.0033 to 0.05 mg/L (**Figure 3A**). It is evident from the results that the maximum presence of As (0.05 mg/L) was found in RWP2 and RWP 18. In comparison, minimum (0.0033 mg/L) was recorded in sample RWP11. The results showed that the presence of As in water is above the limits of WHO standards (i.e., 0.01 mg/L) in all water samples, but only one sample from the district is within the set limits. The findings of the current study are consistent with those of (Cheng *et al.* 2004), who documented water arsenic levels surpassing the World Health Organization's threshold.

3.2.2. Lead (Pb)

Statistical analysis reveals that water samples collected from various regions of the Rawalpindi district exhibit concentrations ranging from 0.0033 mg/L to 0.03 mg/L (**Figure 3B**). It is evident from the results that maximum presence of Pb (0.03 mg/L) was found in RWP20 while minimum 0.0033 mg/L was recorded in sample RWP7 & RWP14. The findings indicated that the concentration of Pb in the water exceeded the thresholds set by WHO standards. However, the values for RWP1, RWP6, RWP7, RWP14, and RWP17 were found to be below the allowable limit, as depicted in **Figure 3B**. The results acquired from the current investigation are consistent with the findings of (Cheng *et al.* 2004) which documented the presence of lead in water surpassing the WHO limit.

3.2.3. Nickel (Ni)

Statistical analysis depicts that water samples ranging from 0.73 to 4.11 mg/L were collected from different areas of the district Rawalpindi (**Figure 3C**). It is evident from the results that the maximum presence of Ni (4.11 mg/L) was found in RWP11, while a minimum of 0.73 mg/L was recorded in samples RWP1 & RWP 7. The results indicated that the concentration of Ni in the water exceeds WHO standards. The results acquired from the current investigation align with those of a study conducted by (Cheng *et al.* 2004), which documented nickel concentrations in water surpassing the PSQCA threshold 3. The result regarding presence of Chromium (Cr) in water samples collected from various regions of the Rawalpindi district contain concentrations ranging from 0.02 to 0.357 mg/L (**Figure 3D**). It is evident from the results that maximum presence of Cr (0.357) was found in RWP3 while minimum 0.02 mg/L was recorded in sample RWP7, RWP12, RWP14 and RWP16. The findings indicated that certain samples contained Cr levels exceeding the WHO standards, whereas eleven out of twenty-one samples remained within the WHO limit. The results acquired from the current investigation are in opposition to the conclusions drawn by (Cheng *et al.* 2004), which documented chromium levels in water surpassing the thresholds set by the PSQCA and WHO.

3.2.4. Copper (Cu)

Statistical analysis reveals that water samples collected from various regions of the Rawalpindi district exhibit concentrations ranging from 0.01 mg/L to 0.05 mg/L (**Figure 3E**). It is evident from the results that maximum presence of Cu (0.05 mg/L) was found in RWP4 while minimum 0.01 mg/L was recorded in sample RWP4. The findings indicated that the concentration of Cu in water does not exceed the thresholds set by the PSQCA and WHO. The results acquired from the current investigation align with those of (Cheng *et al.* 2004) whose study documented the existence of copper in water at concentrations below the WHO threshold.

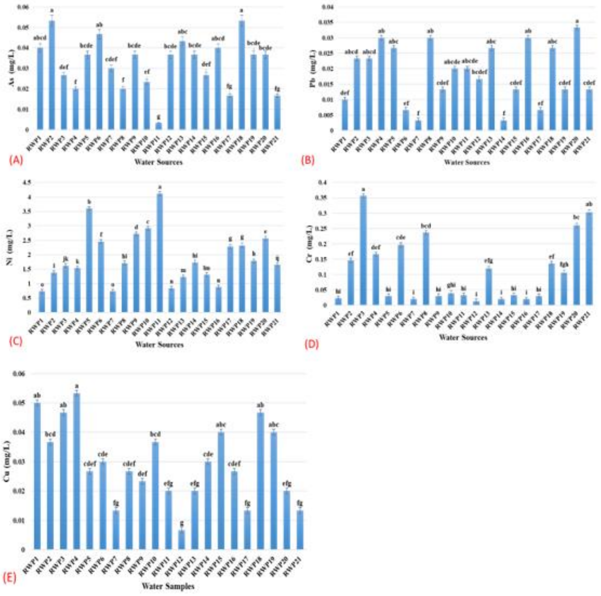


Figure 3. Quantitative analysis of selected heavy metals in water samples collected from 21 areas of Rawalpindi: (A) As, (B) Pb, (C) Ni, (D) Cr, and (E) Cu

3.3. Characterization of Mentha Mediated Iron Nanoparticles

3.3.1. UV-vis spectrum

Utilizing *menthe* to formulate the UV-Vis spectrum of iron nanoparticles provides a valuable resource for comprehending the nanoparticles' optical properties (**Figure 4A**). As the wavelength of the light decreases, the absorbance of light by the nanoparticles increases in the UV spectrum. This is because the nanoparticles absorb shorter wavelengths of light with greater intensity. As shown in **Figure 4A**, the nanoparticles' peak absorbance occurred at approximately 300 nm, indicating that they are minute and highly crystalline.

3.3.2. Scanning Electron Microscopy

The Scanning Electron Microscope (SEM) image illustrates that the iron oxide nanoparticles predominantly exhibit a spherical morphology (**Figure 4B**). Most of these nanoparticles are spherical, although a few exhibit a cubic shape. Additionally, the SEM analysis reveals that the nanoparticles tend to agglomerate. This agglomeration is attributed to the sample being in solution form during the observation and to inadequate drying on the electric slab. The observed clustering indicates that the nanoparticles have not entirely separated from each other, likely due to the presence of residual solvent and the conditions under which the sample was prepared and dried.

3.3.3. Fourier Transform Infrared Spectroscopy

The absorption bands of the samples' diverse functional groups were illustrated on a graph of the FTIR spectra of iron nanoparticles formulated with *Mentha* (**Figure 4C**). These groups may consist of, among others, hydroxyl, carbonyl, and amide groups. Researchers can obtain insights into the chemical composition and structure of the sample through the examination of the peak positions and intensities of these bands.

The broad peak at 3460.06 cm^{-3} indicated the potential existence of stretching vibrations between O-H or N-H. The presence of aliphatic C-H stretching vibrations, which are frequently linked to alkanes or alkyl groups, was indicated by the peak at 2918.10 cm^{-3}. The presence of a carbonyl group (C=O), which is prevalent in compounds such as ketones, aldehydes, carboxylic acids, and esters, was indicated by the peak (1791.75 cm^{-3}). The peaks observed at 1508.23 cm^{-3} and 1635.52 cm^{-3} were indicative of C=C stretching vibrations, which further suggested the existence of a double bond. These may consist of aromatic compounds. The 1541.02 cm^{-3} peak indicated the existence of an amide group, which is prevalent in proteins and peptides. Conversely, the 1458.08 cm^{-3} and 1384.79 cm^{-3} peaks indicated C-H bending vibrations, which are characteristic of alkanes.

3.3.4. EDX

Energy Dispersive X-ray (EDX) microscopy is employed to determine the elemental composition of a sample (**Figure 4D**). In this study, the EDX analysis confirmed the presence of Iron nanoparticles by identifying a prominent peak at 6.5 and 6.9 keV, corresponding to Iron. **Figure 4D** shows the EDX spectrum of FeNPs synthesized using the green method, demonstrating a substantial presence of Iron metal with other impurities such as Mg, S, O, K, Ca, P, N, and C. The spectrum indicates that Iron is present in the nanoparticles, affirming the successful synthesis of Iron nanoparticles. In the synthesis of iron oxide nanoparticles, impurities detected by EDX may originate from the precursor materials, the synthesis environment, or post-synthesis processing. For instance, the presence of elements such as C and O is commonly observed due to the organic solvents used in the synthesis process or from atmospheric absorption. These results are consistent with findings from previous research by (Saif *et al.* 2019), which also highlighted the significant presence of Iron in FeNPs. This validation supports the accuracy and reliability of the green synthesis method used in this study.

3.3.5. XRD

The XRD pattern of the green-synthesized FeNPs, revealing reflections characteristic of a face-centered cubic (FCC) crystalline structure of Iron metal (**Figure 4E**) It can be clearly seen from the figure that FeNPs nanostructure showed high intensity peaks when sonication power was passed 20 W. The patterns showed strong peaks at 115º. Analysis using Origin Pro software identified one prominent diffraction peaks at 115º, corresponding to the FCC structure of Iron. The pattern peaks can be indexed to the mixture of iron oxides nanoparticles according to FCC. The sharp and intensity of peaks designate well crystalline nature of the natural iron oxide nanoparticles. Similar studies elsewhere found by (Saif *et al.* 2019).

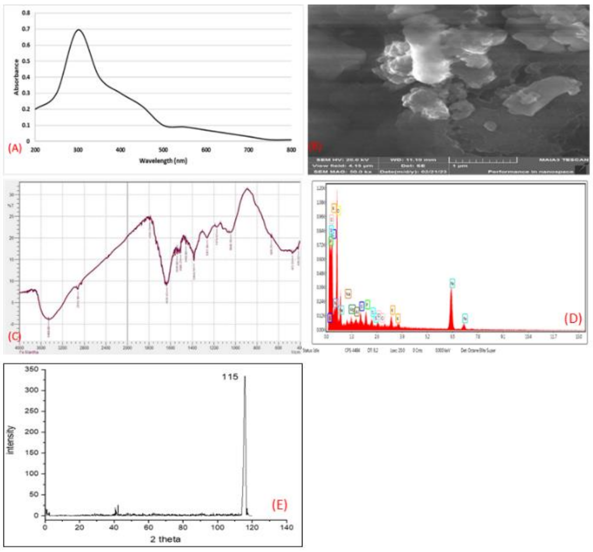


Figure 4. Characterization of mentha-mediated iron nanoparticles (FeNPs) (A) UV spectroscopy, (B) SEM, (C) FTIR spectrum, (D) EDX, (E) XRD

3.4. Removal of heavy metals using FeNPs through adsorption.

3.4.1. Arsenic (As)

According to statistical analysis, the extent of arsenic eradication has varied between 37% and 72%. The results clearly indicate that the highest percentage of as removal (72%) occurred when 1.25 mg was applied for a reaction/contact time of 75 minutes, whereas the lowest percentage (37%), was observed when 0.25 mg was applied for a duration of 15 minutes. The findings demonstrated that the elimination of As from water has substantial implications for the production of potable water. The results acquired from the current investigation were consistent with the prior discovery made by (Abbasi *et al.* 2020, wherein they documented the robust adsorption, high surface reactivity, and magnetic characteristics of Fe_2O_3 nanoparticles that demonstrated remarkable efficacy in eliminating arsenic for water decontamination. (Prasad *et al.* 2014) reported that mint extract-based iron nanoparticles removed 99.65% arsenate from the solution. The adsorption potential of green synthesized iron oxide nanoparticles were evaluated against arsenic contaminated sludge and depited that FeONPs showed 38.48 mg/g sorption capacity (Saif *et al.* 2019) (**Figure 5A**).

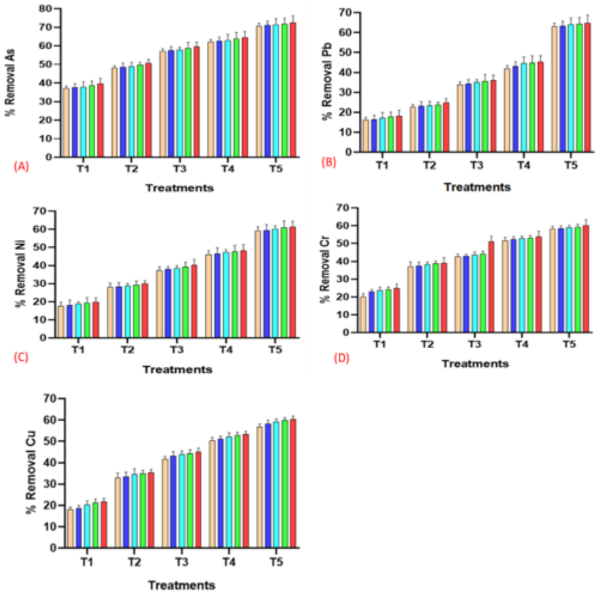


Figure 5. Effect of contact time and adsorbent dose on removal of selected heavy metals from water samples: (A) Removal of as (B) Removal of Pb, (C) Removal of Ni, (D) Removal of Cr, (E) Removal of Cu.

3.4.2. Lead (Pb)

The data from statistical analysis indicates that lead removal has varied between 16% and 65%. The results indicate that the highest percentage of Pb removal (65%) occurred when 1.25 mg was applied for a reaction/contact time of 75 minutes. In contrast, the lowest percentage (16%) was removed when 0.25 mg was applied for a duration of 15 minutes. The results acquired from the current investigation were consistent with the prior discovery made by (Imtiaz *et al.* 2020), wherein they documented the formidable adsorption, strong surface reactivity, and magnetic characteristics of Fe_2O_3 nanoparticles that demonstrated remarkable efficacy in eliminating lead for water decontamination. In another study, green synthesized zero valent FeNPs was used for the significant removal of the lead up to 79.18% from contaminated water after 24 h exposure because of various adsorption active sites found in nZVI-NPs (Jabeen *et al.* 2013).

3.4.3. Nickel (Ni)

The outcomes revealed that the percentage of nickel removal varied between 17.5% and 61%. Maximum Ni removal (61%) was observed when 1.25 mg was applied for 75 minutes of reaction/contact time; minimum Ni removal (17.5%) was observed when 0.25 mg was applied for only 15 minutes, as indicated by the results. The findings of the current study were consistent with those of (Moodley *et al.* 2011), who documented the strong adsorption, high surface reactivity, and magnetic properties of an agricultural adsorbent that was found to be highly effective in their investigation of nickel removal for water decontamination.

3.4.4. Chromium (Cr)

According to statistical analysis, chromium removal has varied between 20% and 60%. The findings indicate that the highest percentage of Cr (60%) was eliminated using

1.25 mg for a reaction/contact time of 75 minutes, whereas the lowest percentage (20%) was eliminated using 0.25 mg for a duration of 15 minutes. The results acquired from the current investigation were consistent with the prior discovery made by (Weng *et al.* 2016), wherein they documented the strong adsorption, high surface reactivity, and magnetic characteristics of Fe_2O_3 nanoparticles that demonstrated remarkable efficacy in eliminating chromium for water decontamination.

3.4.5. Copper (Cu)

The outcomes revealed that, the percentage of copper removed has varied between 15% and 60%. The results clearly indicate that the highest percentage of Cu (60%) removal occurred when 1.25 mg dose was applied for a reaction/contact time of 75 minutes. In contrast, the lowest percentage removal (20%) occurred when 0.25 mg was applied for 15 minutes. The results acquired from the current investigation were consistent with the prior discovery made (Imtiaz *et al.*, 2020), which documented the strong adsorption, high surface reactivity, and magnetic characteristics of Fe_2O_3 nanoparticles. These nanoparticles were highly effective in removing copper for water decontamination purposes. (Weng *et al.* 2016) conducted a study and demonstrated that eucalyptus plant extract-based iron nanoparticles have removal efficacy against the hazard contaminants Cr and Cu from wastewater is about 58.9 and 33 %, respectively. The authors proposed that this technique to eradicate the mixed pollutants from wastewater with cost-effective and environment friendly is the sustainable solution in contaminated waterways.

4. Discussion

As heavy metals have a significant potential for toxicity, they are typically seen as a risk to both environments and humans. The human body needs very small amounts of heavy metals including copper, chromium, zinc, manganese, and iron to function. However, if the metals accumulate at certain levels, they might lead to poisoning, which can have dangerous consequences for human health (Baloch *et al.* 2023). The physicochemical characteristics of drinking water have been the part of research studies for assessing the quality and safety of water for human consumption. In our research, pH, hardness, total soluble solids, electrical conductivity, and turbidity were studied as physicochemical properties of drinking water. The results are mentioned above under each characteristic of the sample water. The pH of drinkable water indicates its alkalinity or acidity. Drinking water must maintain an appropriate pH level to maximize flavor and health. Water below 7 pH is acidic due to dissolution of iron, manganese, and copper in the water source. Acidic chemical usage and industrial emissions may also lower pH. Acidic water tastes sour, corrodes plumbing, and releases metals. In contrast, alkaline water has a pH above 7, possibly due to minerals like calcium, magnesium, and bicarbonate. Extremely high pH levels can leave a harsh taste and deposit on plumbing fittings, unlike moderately alkaline water, which may taste good. High and low pH levels in drinkable water can impair human health. Extremely alkaline water can worsen mineral imbalances, while potassium-acidic water can cause gastrointestinal upset. To ensure safe and tasty drinking water, pH levels must be tested often. The optimal pH range for drinking water is 6.5 to 8.5, which can be achieved by filtering and adding alkaline chemicals.

Hardness is determined by water mineral concentration, mostly calcium and magnesium ions. This criterion affects drinkable, household, and industrial water cleanliness, making it important. Water hardness is determined chiefly by its geology. Groundwater is harder than surface water because it passes through magnesium and calcium bedrock. Human actions like using detergents and fertilizers may also harden water. Hard water is routinely softened via ion exchange and chemical precipitation that precipitates calcium and magnesium ions. Monitoring and remediation can reduce water hardness's negative effects.

TDS, a critical metric, measures water's dissolved material concentration. In our analysis, certain samples exhibited greater results than (Javed and Mashwani 2020), possibly due to larger urban discharge into groundwater and being unfit for human consumption as per PSQCA standard of 1000 mg/L. TDS concentrations in water vary greatly depending on environmental conditions and source. Urban runoff, industrial discharges, agricultural runoff, and industrial discharges may also increase TDS and pollutant levels. Increased TDS levels can affect drinkable water taste, odor, and quality. Instead, drinkable water with low TDS is preferred for its purer taste. Conversely, a very low TDS value may indicate a mineral shortage, affecting palatability and requiring which mineral supplements. Potable water safety, palatability, and lack of contaminants, especially excessive dissolved solids or chemicals, require consistent monitoring, appropriate remediation solutions, and ecologically responsible activities.

Due to dissolved ions, water's electrical conductivity allows electric current to flow. It is often used to assess water quality by representing water ion concentration. The absence of ions makes pure water electrically non-conductive. In contrast, lakes, rivers, and groundwater contain conductive dissolved minerals. Water electrical conductivity may increase when dissolved chemicals like salt, chloride, sulfate, and carbonate are present. Adding ions increases conductivity through agricultural wastewater, industrial discharges, and urban pollution. Water with moderate electrical conductivity is generally safe to drink. However, high conductivity can cause an unpleasant taste and indicate contaminants. Electricity conductivity helps assess water quality and identify dissolved ion issues.

Water turbidity is caused by suspended particles like sediment, clay, organic substances, and microscopic organisms. Many natural and manmade processes create water turbidity. Natural causes include soil erosion, algal outbreaks, and sediment resuspension. Human activities like construction, deforestation, agricultural runoff, and wastewater discharges may increase turbidity. Because germs may stick to surfaces and defend themselves, turbidity may include harmful infections. Low-turbidity drinking water decreases microbiological contamination and is aesthetically pleasing. In our study, all water samples have turbidity within the threshold level except one sample RWP20) due to the presence of discharge effluents. It was reported that nanoparticle filtration also decreases the turbidity of the water because it diminishes the light scattering capability of water and confirms that nanoparticles remove the bunches of fungi, algae, and another microorganism from the water (Javed and Mashwani 2020).

The presence of metallic ions in drinking might be beneficial for human use but within a certain limit. Metals belonging to the toxin category may cause serious troubles for humans after limited use. In our research, the presence of arsenic (As), lead (Pb), nickel (Ni), chromium (Cr), and copper (Cu) was studied in collected samples of water from Rawalpindi, a district of Pakistan.

The health risks of arsenic in drinkable water are serious. Groundwater naturally contains arsenic, especially in geologically distinct locations. It can also enter waterways from mining, industrial processes, and pesticide use. Even at low doses, arsenic can cause lung, epidermal, bladder, and skin cancers, cardiovascular issues, and neurological impairments. The WHO and PSQCA suggested a drinking water arsenic level of 0.01 mg/L and 0.05 mg/L respectively to protect public health. Consistent water source testing helps identify polluted areas and enable remediation.

Lead in drinking water is a public health concern due to its possible health risks, especially for children. Lead pipelines, plumbing fittings, and solder can corrode and leach lead into drinking water. The WHO and PSQCA suggest a maximum lead limit of 0.01 mg/L and 0.05 mg/L to protect public health. Lead exposure can cause serious health problems at low doses. Children can acquire cognitive, behavioral, and developmental difficulties from lead-contaminated water. Lead exposure in adults may cause cardiovascular and kidney problems.

Anthropogenic, natural, and industrial discharges can introduce nickel into water sources, even though it is rarely associated with water contamination. The PSQCA limits nickel in drinkable water at 0.02 mg/L. Nickel over exposure may harm human health, causing skin sensitivities, respiratory issues, and cancer. Nickel can cause cutaneous reactions in nickel-allergic people, even in trace levels. Chromium, a metallic element, has many oxidation states, but III and VI are the most common. Due to its toxicity and health risks, chromium in drinkable water, especially hexavalent chromium (VI), is a problem. According to the WHO, total chromium in drinking water should not exceed 0.05 mg/L.

Water contains accidental copper from human and natural processes. Copper is essential in trace amounts, but excessive concentrations in drinkable water may be harmful for health. The WHO recommends limiting potable water copper content to 2 mg/L to avoid gastrointestinal issues. Copper overdose can cause nausea, gastrointestinal distress, and liver and kidney damage. Safe water practices, including education and public awareness campaigns about heavy metals in drinkable water, may be helpful to overcome the pollution process. To fight heavy metal poisoning, public health programs, water treatment technologies like use of nanoparticle adsorption, and routine testing are needed. To preserve the health and welfare of communities that use these water sources, heavy metals regulations must be followed.

The reported data have presented that plant extract-based synthesized iron nanoparticles had better adsorption efficiency (69%) As compared to the other methods based on synthesized nanoparticles (Mukherjee *et al.* 2016). The green synthesis process involved many parameters including extract volume, salt solution, time of reaction and reaction temperature, might have the effects on size and shape of FeNPs crystal. Out of which, extract of *mentha*affect iron nanoparticle optical characteristics during production. Mentha's aromatic chemicals may reduce nanoparticle size and form. In general, Mentha-synthesized iron nanoparticles' UV spectrum revealed their optical properties. This data can improve synthesis and provide new nanoparticle applications in sensing, catalysis, and healthcare. A powerful analytical technology, FTIR is used to detect and analyze the chemical content and structure of many compounds. FTIR study of iron nanoparticles formed with *Mentha*revealed chemical connections and interactions between the nanoparticles and the extract. SEM images showed that nanoparticles were in crystalline structure and aggregated form. Our results are aligned with the previous one, which reported that iron nanoparticles synthesized from cherry, mulberry, and oak leaf extracts showed significant adsorption potential against heavy metals. The adsorption studies exposed that these NPs are more pronounced adsorbents that follow pseudo-second-order kinetics (Ghaemi *et al.* 2015).

The efficacy of the chosen adsorbent in eliminating heavy metals, including As, Pb, Ni, Cr, and& Cu, was critical in the advancement of viable and environmentally conscious approaches to water treatment. The mechanisms behind the adsorption of iron nanoparticles from contaminated water include ligand-ion tandem, surface binding, electrostatic interaction among pollutants and magnetic nanoparticles due to the presence of various biomolecules on nanoparticle surfaces, surface precipitation, and ion exchange predominantly facilitated by the presence of various functional groups (Pan *et al.* 202).

The results of this research made a valuable contribution to the continuous endeavors aimed at mitigating the adverse health impacts caused by heavy metal contamination. This research investigated one of the novel heavy metal removal methods that has the potential to remove a maximum quantity of heavy metals, specifically in regions confronted with heavy metal-related obstacles. The practical implications of the findings for water treatment technologies underscore the criticality of ongoing progress in environmental remediation.

5. Conclusion

The present study successfully demonstrates the synthesis of Mentha-mediated iron nanoparticles and their application as an innovative adsorbent for the removal of heavy metals from water. The data analysis suggested that the comprehensive characterization of FeNPs confirmed the successful formation of uniformly distributed nanoparticles with well-defined morphologies. Gaining insight into the efficacy of FeNPs in eliminating heavy metals is critical in pursuing efficient and environmentally viable water treatment techniques. The adsorbing potential of these NPs was substantiated by ICP-OES analysis, which showed a significant reduction (60%) in heavy metals concentration. The findings of this research have the potential to provide significant contributions to the domain of environmental remediation, thereby establishing a potential pathway for implementing green mediated FeNPs in heavy metal removal offering a sustainable solution for addressing environmental pollution. This study presents a correlation with current endeavors to tackle water quality concerns and emphasizes the importance of inventive resolutions in guaranteeing potable water that is both secure and readily available for populations across the globe. In summary, the research results suggest that the water contamination in the examined region presents a persistent health hazard. Nevertheless, because certain heavy metals surpassed their maximum allowable concentrations, it is advisable to refrain from consuming water from contaminated locations until it has undergone treatment. In the event that this does not occur, the Pakistani government may provide alternative water sources to the affected regions. Future research should focus on assessing the long-term stability and environmental impact of nanoparticles for scalable water treatment applications and evaluate the effect of NPs on water quality improvements.

Declarations and Statements

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Conflict of Interest

The authors declare no personal or financial conflict of interest.

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