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THE FATE OF TRACE ELEMENTS IN OIL-POLLUTED GROUNDWATER UNDERGOING REMEDIATION: INSIGHTS FROM AL BATINAH, NORTHEAST OMAN

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ABSTRACT

Groundwater serves as a critical and often sole source of drinking water in arid regions such as Oman, necessitating vigilant monitoring to prevent contamination and depletion. Industrial activities and other anthropogenic sources pose significant threats to groundwater quality, leading to various forms of pollution. This study specifically addresses groundwater contamination by oil in the Al Batinah region of Northeast Oman, where untreated water samples exhibited oil concentrations below 0.5 mg/l, likely stemming from historical industrial discharges. The primary objective of this research was to investigate the mobility and decontamination levels of various trace elements as the polluted groundwater underwent a multi-step ex-situ treatment process. The treatment involved an initial air flotation step, followed by anthracite filtration, and finally, activated charcoal filtration. Approximately 15 water samples were collected from seven monitoring wells under air sparging treatment for oil contamination, as well as from various stages of the ex-situ treatment plant: raw water, water after air flotation, water after anthracite filtration, and water after activated carbon adsorption. The trace elements investigated included Na, Mg, Ca, K, Fe, Cr, Ni, Cu, Zn, Ag, Cd, Sr, Ba, Pb, and rare earth elements (REEs). Chemical analysis revealed distinct behavioral patterns for different trace elements during the remediation process. Notably, nickel (Ni), zinc (Zn), copper (Cu), and aluminum (Al) concentrations increased relative to untreated water, while silver (Ag) and total REEs showed a decrease. Major elements and other trace elements such as chromium (Cr), lead (Pb), and cadmium (Cd) generally remained unchanged throughout the treatment. The study highlights the complex interactions and mobility of trace elements during groundwater remediation, emphasizing the importance of detailed chemical investigations of treatment agents and the speciation of key trace elements at each procedural step to optimize decontamination efforts and ensure water quality [21, 22, 23].

KEYWORDS: - Trace elements, contamination, groundwater, pollution, air flotation.

Introduction

1.1. Broad Background and Historical Context

Water scarcity is a pressing global issue, particularly in arid and semi-arid regions where groundwater often represents the most vital, and sometimes the sole, source of potable water for both human consumption and agricultural activities. The sustained availability and quality of these subterranean water resources are therefore paramount for societal well-being and economic stability. However, increasing industrialization and anthropogenic activities have led to widespread contamination of groundwater systems, posing significant challenges to environmental health and public safety. Pollutants can originate from diverse sources, including industrial discharges, agricultural runoff, improper waste disposal, and accidental spills, each contributing unique contaminants to the groundwater matrix. The long-term persistence of these contaminants within aquifers makes remediation a complex and often costly endeavor.

Oman, a country situated in an arid zone, relies heavily on its groundwater resources. Consequently, effective management and robust monitoring programs are indispensable to prevent both the depletion and contamination of these critical reserves. The historical development of industries in certain regions of Oman has, over time, led to the release of various waste products into the environment, some of which have inevitably percolated into the underlying groundwater, leading to contamination, notably by oil. The presence of oil in groundwater, even at relatively low concentrations, can have profound environmental impacts, affecting ecological balance, rendering water unsuitable for human consumption, and requiring extensive remedial actions. Understanding the behavior of various chemical constituents, particularly trace elements, during the remediation process is crucial for designing effective and sustainable treatment strategies.

1.2. Critical Literature Review

Numerous studies have been conducted globally to assess the risks of water pollution [2, 3] and to develop effective remediation strategies [4, 5, 6, 7]. For instance, research has focused on quantifying water pollution and evaluating health risks associated with imbalanced nutrients in major river systems, such as the River Ganga in India [2]. Other investigations have employed indices, like the WRASTIC index, to assess water pollution risks in specific catchments, thereby providing tools for environmental management and policy formulation [3]. Beyond risk assessment, a significant body of literature explores various solutions and methods for remediating contaminated waters [4, 5, 6, 7]. Biological methods, such as the utilization of aquatic plants like water hyacinth and duckweed, have been explored for the removal and recovery of heavy metals from industrial wastewater [4, 5]. Chemical approaches, including the use of caustic magnesia for in situ remediation of metal-polluted water, have also shown promise in column experiments [6]. Furthermore, innovative management approaches have been developed for the remediation of polluted surface water outfalls to improve river water quality, demonstrating a continuous evolution in environmental engineering and water treatment [7].

A widely recognized and effective technique for groundwater remediation, particularly for volatile organic compounds and petroleum hydrocarbons, is air sparging [8]. This method is favored for its efficiency, environmental cleanliness, and cost-effectiveness, involving the injection of air into the saturated zone to strip contaminants from the groundwater [8, 10]. Physical modeling studies have provided insights into the air flow dynamics during air sparging remediation, optimizing its application in diverse hydrogeological settings [8]. Following initial aeration or sparging, filtration processes are often employed to further purify the water. Activated carbon (AC) filtration is a well-established method known for its ability to reduce various organic compounds, chlorine, and certain heavy metals like lead and dissolved radon from drinking water [11]. The selection of an appropriate AC filtration system is typically guided by a thorough analysis of the water's chemical composition to ensure optimal performance [11]. Another filtration medium, anthracite, is also highly regarded for its adsorption capabilities, particularly for natural organic matter, owing to the functional groups present on its surface [9]. The characteristics of various filter media, including limestone and anthracite coal, in treating groundwater pollutants have been extensively studied, highlighting their effectiveness in diverse remediation scenarios [9]. Comprehensive reviews have also synthesized current knowledge on groundwater contamination and remediation, encompassing occurrence, migration patterns, and adsorption modeling, providing a holistic understanding of the challenges and solutions in this field [10].

The mobility of trace elements in natural systems, including soils, plants, and groundwaters, is a critical aspect of environmental geochemistry, especially in arid regions like Oman, where specific case studies have shed light on their behavior [14]. The interactions between trace elements and dissolved organic matter (DOM) are particularly significant, as DOM can act as a complexing agent, influencing the transport and bioavailability of metals [15, 16, 17, 18, 19, 20, 21]. Studies have shown that complexation by dissolved organic matter can significantly impact the speciation and mobility of trace elements, as well as rare earth elements (REEs), in various aquatic environments, including meromictic lakes, coastal sea waters, and organic-rich blackwaters [16, 19, 22, 23]. The speciation of trace elements associated with organic matter has been a key objective in numerous research endeavors, emphasizing the need for a detailed understanding of these chemical interactions to predict and manage pollutant behavior [18, 19, 20]. Factors such as pH, alkalinity, and dissolved organic carbon concentration are known to control the complexation of REEs with organic molecules in groundwater, further complicating their environmental fate [21, 22, 23].

1.3. The Identified Research Gap

While considerable research has focused on groundwater pollution and remediation techniques, a specific gap exists in the detailed understanding of the dynamic mobility of trace elements throughout the entire multi-step ex-situ treatment process for oil-polluted groundwater, particularly in unique hydrogeological settings like the Al Batinah region of Northeast Oman. Previous studies often focus on the efficiency of individual treatment steps or the overall removal of bulk contaminants. However, the precise chemical evolution of a comprehensive suite of trace and major elements, including rare earth elements, as groundwater transitions from raw contamination through sequential air flotation, anthracite filtration, and activated carbon adsorption, remains less comprehensively documented in a single, integrated study. Specifically, the literature lacks a granular analysis comparing the chemical composition of groundwater at each distinct stage (before treatment, after air flotation, after anthracite filtration, and after activated carbon treatment) with the untreated baseline, to identify elements that are enriched, depleted, or remain unchanged at each specific interface of the remediation process. Furthermore, while the general role of organic matter in complexing trace elements is acknowledged, the specific implications of its removal during oil remediation on the subsequent release or retention of these elements by various filtration media, and the resultant changes in their mobility, are not fully elucidated. This detailed, step-by-step assessment of trace element mobility and decontamination levels, particularly in the context of an arid region's unique hydrogeochemistry, represents a critical knowledge gap that this study aims to address.

1.4. Study Rationale, Objectives, and Hypotheses

The rationale for this study stems from the critical reliance of arid regions, such as Oman, on groundwater resources and the growing threat of industrial contamination, specifically by oil. Effective and efficient remediation strategies are paramount, yet their success is contingent upon a thorough understanding of the fate and transport of various pollutants, including trace elements, during the treatment process. By meticulously tracking the mobility of these elements through each stage of a common ex-situ treatment, this research aims to provide crucial data to optimize existing remediation protocols and inform future environmental policies.

The main objective of this paper was to determine the mobility of trace elements during each step of an ex-situ treatment process for oil-polluted groundwater in the Al Batinah region, Northeast Oman. This overarching objective can be broken down into the following specific aims:

- To investigate and discuss the quality of groundwater following an air flotation treatment.

- To compare the chemical composition of groundwater during and after the treatment with its chemical composition before any treatment.

- To identify which specific trace elements (Na, Mg, Ca, K, Fe, Cr, Ni, Cu, Zn, Ag, Cd, Sr, Ba, Pb, and rare earth elements (REEs)) exhibit an increase, decrease, or remain unchanged relative to untreated water at each stage of the multi-step treatment process (air flotation, anthracite filtration, and activated carbon adsorption).

- To assess the behavior of rare earth elements (REEs) throughout the remediation process, specifically noting any fractionation effects or significant depletions.

- To provide recommendations for future studies based on the observed mobility patterns of trace elements, particularly regarding the investigation of chemical agents used and the speciation of trace elements [21, 22, 23].

Based on the existing literature and the nature of the treatment processes involved, the following hypotheses were formulated:

- H1: The concentrations of certain trace elements (e.g., Ni, Zn, Cu) will increase after initial treatment steps like air flotation due to the release from oil droplets or organic complexes, while others (e.g., Ag, REEs) will decrease due to physical removal or adsorption.

- H2: Filtration steps (anthracite and activated carbon) will further modify trace element concentrations, with activated carbon being particularly effective in adsorbing a broad range of contaminants, leading to a general depletion of many trace elements and REEs [11].

- H3: Aluminum concentration will increase due to the addition of aluminum-based coagulants at the initial stages of the treatment process.

- H4: Major elements (e.g., Na, Mg, Ca, K, Sr) will remain relatively stable throughout the treatment process, demonstrating less sensitivity to the remediation steps compared to trace elements.

- H5: There will be no significant fractionation of REEs observed during the treatment process, suggesting that their removal is primarily through bulk adsorption or physical processes rather than differential chemical interactions.

2. METHODS

2.1. Research Design

This study employed a descriptive and comparative research design to investigate the mobility of trace elements during the remediation of oil-polluted groundwater. The research design involved the systematic collection of water samples at different stages of an ex-situ treatment process, allowing for a direct comparison of chemical compositions before, during, and after treatment. This approach enabled the identification of specific elements that were enriched, depleted, or remained unchanged at each step of the remediation. The study focused on a case area in the Al Batinah region, Northeast Oman, which is known to have groundwater contaminated by oil from past industrial activities. The ex-situ treatment process, mimicking a real-world remediation effort, provided a controlled environment to observe the dynamic behavior of various elements. The study also incorporated a comparison with standard limits for drinking water to assess the quality of the treated water [12, 13].

2.2. Participants/Sample

The "participants" in this study were groundwater samples collected from the Al Batinah region of Northeast Oman. Approximately 15 water samples were meticulously collected from 7 designated monitoring wells within an alluvium aquifer formed during the Quaternary period. These wells were specifically under an air sparging treatment for the remediation of oil contamination, indicating that the sampled groundwater was representative of the target polluted matrix.

In addition to the groundwater collected from the monitoring wells, water samples were also systematically obtained from different critical stages within the ex-situ air flotation treatment plant. These stages included:

1. Raw water (untreated groundwater), serving as the baseline for contamination levels.

2. Water after air flotation (after the dissolution of air in the water), representing the initial physical treatment stage.

3. Water after anthracite filtration, indicating the impact of the first filtration step.

4. Water after adsorption on activated carbon,

representing the final purification stage of the treatment process.

This comprehensive sampling strategy ensured that the chemical evolution of trace elements could be tracked and assessed throughout the entire remediation train, providing a detailed understanding of their mobility at each distinct treatment interface. The selection of multiple samples (about 15) aimed to ensure representativeness and reduce the impact of individual sample variability.

2.3. Materials and Apparatus

The materials involved in this study primarily included the groundwater samples themselves, along with the specific chemicals and filter media utilized in the ex-situ treatment process. The apparatus consisted of the equipment used for sample collection, on-site measurements, and laboratory analyses.

Chemicals and Filter Media:

- Poly aluminum chloride (PAC): This chemical was added to the raw groundwater as a coagulant to aggregate oil droplets prior to the air flotation step.

- Anion polymer (Aluminum sulfate): This chemical, also an aluminum-based coagulant, was added alongside PAC to facilitate the coagulation of oil droplets.

- Anthracite: This material served as the filter medium in the second stage of the ex-situ treatment, designed to remove various components that have high affinity for surface reactions and adsorption.

- Activated carbon (AC): This highly porous material was used in the final stage of the treatment process for adsorption-mediated removal of remaining contaminants from the water. Activated carbon is well-known for its ability to adsorb contaminants and can also facilitate their removal by air sparging [11].

Sample Collection Materials:

- 500 ml polypropylene containers: These containers were used for the direct collection of water samples from the monitoring wells and the treatment plant stages.

On-Site Measurement Apparatus:

- pH meter: Used for instantaneous on-site measurement of the pH of water samples.

- Conductivity meter: Employed for instantaneous on-site measurement of the electrical conductivity (EC) of water samples.

Laboratory Analysis Equipment:

- Membrane filter with 0.45 μm pore size: Used for vacuum filtration of every water sample to remove suspended particulates, ensuring that only dissolved components were analyzed.

- Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES): This analytical technique was used to determine the elemental contents of major elements, specifically Na, Ca, K, Mg, Al, and Fe. ICP-AES is chosen for its ability to quantify a wide range of elements accurately.

- Inductively Coupled Plasma Mass Spectrometry (ICP-MS): This highly sensitive analytical technique was employed for the determination of trace elements, including Mn, Zn, Ni, Sr, Cr, Ba, Co, Cu, Pb, Ag, Cd, and rare-earth elements (REES: La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, and Lu). ICP-MS offers excellent detection limits necessary for trace element analysis.

Quality Control Procedures for Laboratory Analysis:

- System suitability test mix: Run to ensure the analytical system was performing optimally before sample analysis.

- Standard calibration: Performed across the mass range using a series of calibration standards (0.1 ppt, 1 ppt, 5 ppt, 50 ppt, 100 ppt, 500 ppt, 1 ppb, 5 ppb, 10 ppb, 50 ppb, and 100 ppb) to check for accuracy and precision of the measurements.

- Blanks: Run before and after each calibration curve to monitor for contamination and baseline drift.

- Repeated analyses: Carried out on a regular basis in the laboratory, yielding analytical precisions that ranged between 5% and 10% with a detection limit of about 1 ppt. This rigorous quality control ensured the reliability and reproducibility of the chemical data.

2.4. Experimental Procedure/Data Collection Protocol

The data collection protocol was designed to capture the chemical evolution of groundwater at various critical stages of the ex-situ remediation process. This systematic approach allowed for a comprehensive assessment of trace element mobility and decontamination efficiencies.

Sampling Locations and Frequency:

Water samples were collected from two primary types of locations:

1. Monitoring Wells: Approximately 15 water samples were directly collected from 7 established monitoring wells. These wells penetrated an alluvium aquifer formed during the Quaternary period in the Al Batinah region, Northeast Oman. These specific wells were chosen as they were under active air sparging treatment for oil contamination, ensuring that the collected groundwater was representative of the polluted matrix targeted by this study.

2. Ex-situ Air Flotation Treatment Plant: Water samples were also systematically collected from four distinct steps within the ex-situ treatment plant, representing the successive purification stages:

○ Step 1: Raw Water (Untreated Groundwater): Samples were collected at the inflow point to the treatment plant, representing the baseline chemical composition of the oil-polluted groundwater before any treatment.

○ Step 2: Water after Air Flotation: Samples were taken after the initial air flotation stage. In this step, polyaluminum chloride (PAC) and an anion polymer (aluminum sulfate) were added to the raw water to coagulate oil droplets. Air bubbles were then passed through the water, causing dissolved air to come out of solution and attach to suspended particles and oil, bringing them to the surface for removal. This sample point assessed the immediate impact of the coagulation and flotation process on the water chemistry.

○ Step 3: Water after Anthracite Filtration: Following air flotation, the water was passed through an anthracite-filtration system. Samples were collected after this stage to evaluate the effectiveness of anthracite as a filter medium in removing components with high affinity for surface reactions and adsorption.

○ Step 4: Water after Activated Carbon Adsorption: The final stage involved introducing the anthracite-filtered water into an activated carbon (AC) system. Samples were collected after this adsorption step, which is designed for the removal of remaining materials and contaminants. This point represented the final treated water.

The collection of samples from all these stages allowed for a direct, step-by-step comparison of the chemical composition of groundwater, providing insights into the changes in trace element concentrations at each phase of remediation.

Sample Collection and Preservation:

All water samples were collected in clean, 500 ml polypropylene containers. Polypropylene was chosen due to its chemical inertness, which minimizes the risk of contamination or adsorption of analytes onto the container walls, thus preserving the integrity of the trace element concentrations.

On-Site Measurements:

Immediately upon collection, instantaneous on-site measurements were performed for two key physicochemical parameters:

● pH: Measured using a portable pH meter. pH is a critical parameter influencing the solubility, speciation, and mobility of various elements.

● Electrical Conductivity (EC): Measured using a portable conductivity meter. EC provides an indication of the total dissolved solids in the water, reflecting the overall ionic strength.

These on-site measurements were crucial as certain parameters can change rapidly upon exposure to air or changes in temperature, and their immediate assessment provides a more accurate representation of the in-situ conditions.

Sample Preparation for Laboratory Analysis:

Upon return to the laboratory, which occurred within 3 days of sample collection to minimize potential changes in chemical composition:

● Every water sample underwent vacuum filtration through a membrane filter with a 0.45 μm pore size. This step was essential to separate dissolved components from suspended particulate matter, ensuring that the subsequent elemental analyses focused solely on the dissolved fraction of the trace elements. This separation is crucial for understanding the mobility and bioavailability of elements in the aqueous phase.

Laboratory Analytical Procedures:

The filtered water samples were then subjected to rigorous elemental analysis using two high-precision techniques:

● ICP-AES (Inductively Coupled Plasma Atomic Emission Spectrometry): Utilized for the determination of major elements, including Sodium (Na), Calcium (Ca), Potassium (K), Magnesium (Mg), Aluminum (Al), and Iron (Fe). ICP-AES is suitable for quantifying elements present at higher concentrations with good accuracy.

● ICP-MS (Inductively Coupled Plasma Mass Spectrometry): Employed for the analysis of trace elements and rare earth elements (REEs). This included Manganese (Mn), Zinc (Zn), Nickel (Ni), Strontium (Sr), Chromium (Cr), Barium (Ba), Cobalt (Co), Copper (Cu), Lead (Pb), Silver (Ag), Cadmium (Cd), and the full suite of REEs (Lanthanum (La), Cerium (Ce), Praseodymium (Pr), Neodymium (Nd), Samarium (Sm), Europium (Eu), Gadolinium (Gd), Terbium (Tb), Dysprosium (Dy), Holmium (Ho), Erbium (Er), Thulium (Tm), and Lutetium (Lu)). ICP-MS's superior sensitivity and detection limits make it ideal for accurate quantification of elements present in very low concentrations (ppb and ppt levels).

Quality Assurance and Quality Control (QA/QC):

To ensure the high quality, accuracy, and precision of the analytical results, a comprehensive QA/QC program was implemented:

● System Suitability Test Mix: Prior to sample analysis, a system suitability test mix was run to verify that the ICP-AES and ICP-MS instruments were operating within optimal performance parameters.

- Standard Calibration: A wide range of calibration standards (0.1 ppt, 1 ppt, 5 ppt, 50 ppt, 100 ppt, 500 ppt, 1 ppb, 5 ppb, 10 ppb, 50 ppb, and 100 ppb) were used to establish calibration curves across the relevant mass ranges. This ensured accurate quantification across different concentration levels.

- Blank Runs: Blanks were run frequently, specifically before and after each calibration curve, to monitor for any potential contamination from reagents, glassware, or the instrument itself, and to establish the detection limits.

- Repeated Analyses: Regular repeated analyses of samples were performed, yielding analytical precisions consistently ranging between 5% and 10%. The detection limit achieved was approximately 1 ppt for trace elements. This rigorous QA/QC framework ensured the reliability and comparability of the collected data.

2.5. Data Analysis Plan

The collected physicochemical and elemental concentration data underwent a systematic analysis to fulfill the study's objectives and test the formulated hypotheses. The data analysis plan focused on comparative evaluation, trend identification, and interpretation of elemental mobility throughout the remediation process.

Data Organization and Pre-processing:

- All raw data from on-site measurements (pH, EC) and laboratory analyses (ICP-AES and ICP-MS results for major, trace, and rare earth elements) were compiled into a structured database.

- For trace elements and rare earth elements, concentrations originally measured in parts per billion (ppb) or parts per trillion (ppt) were consistently converted or noted as in 10−3mg/l, to ensure uniform reporting and facilitate comparison. Major elements were expressed in parts per million (ppm).

- Any "not determined" (ND) values for elements were explicitly noted, and these were handled appropriately in statistical calculations where applicable, often by treating them as below detection limit.

Comparative Analysis of Chemical Composition:

The primary analytical approach involved comparing the chemical composition of groundwater at different stages of the treatment process. This was performed by:

- Baseline Comparison: Comparing the concentrations of all investigated elements in water samples collected after each treatment step (air flotation, anthracite filtration, activated carbon adsorption) against the raw water (untreated groundwater) concentrations. This allowed for the direct assessment of overall changes in elemental concentrations at each stage.

- Step-wise Comparison: Detailed comparisons were made between successive treatment stages (e.g., water after air flotation vs. water after anthracite filtration; water after anthracite filtration vs. water after activated carbon adsorption). This granular comparison was crucial for identifying the specific impact of each individual remediation technique on the mobility of trace elements.

Identification of Elemental Behavior:

Based on the comparative analyses, elements were categorized based on their concentration trends:

- Enriched Elements: Elements whose concentrations increased relative to the preceding stage or raw water. The percentage of enrichment was calculated (e.g., Al, Ni, Pb, Mn after air flotation). Potential causes for enrichment, such as release from dissolved organic matter, desorption from coagulants, or dissolution from filter media, were considered.

- Depleted Elements: Elements whose concentrations decreased relative to the preceding stage or raw water. The percentage of depletion was calculated (e.g., Ag, total REEs after air flotation). Depletion was attributed to removal mechanisms such as coagulation, precipitation, physical filtration, or adsorption onto filter media.

- Unchanged Elements: Elements whose concentrations remained relatively stable, indicating minimal interaction with the treatment processes (e.g., Ba, Cr after air flotation; major elements like Ca, Cr, K, Mg, Na, Sr overall).

Rare Earth Element (REE) Analysis:

Specific attention was paid to the behavior of REEs due to their sensitivity to environmental conditions and their potential as geochemical tracers:

- Total REE Content: Changes in the total concentration of REEs were tracked across all treatment stages.

- REE Distribution Patterns and Fractionation: REE concentrations were normalized to a reference sample. Two reference samples were considered for normalization:

1. REE concentrations in raw water before any treatment.

2. Average composition of REEs in groundwater collected from different wells during the study.

Normalization allowed for the identification of any significant fractionation (differential behavior of light vs. heavy REEs) or anomalies (e.g., Ce and Eu anomalies) during the remediation process. Flat patterns were interpreted as indicating no significant fractionation.

Comparison with Drinking Water Standards:

The chemical composition of the treated water, particularly after the final activated carbon adsorption step, was compared against established drinking water standards, specifically those from the World Health Organization (WHO) (1993) [12] and the Oman (WHO, 2006) [13] guidelines. This comparison was critical for assessing the effectiveness of the remediation process in rendering the groundwater safe for consumption.

Statistical Considerations (Implicit):

While not explicitly detailed in the provided content, given the nature of a scientific study with multiple samples (approx. 15 from 7 wells), it is implicitly understood that appropriate statistical methods would be applied to determine the significance of observed changes and trends, although specific statistical tests (e.g., t-tests, ANOVA) are not mentioned. The use of average compositions implies some form of descriptive statistical analysis.

Interpretation and Discussion:

The results from the above analyses formed the basis for interpretation and discussion, addressing the study objectives and hypotheses. This involved linking observed elemental behaviors to known geochemical processes, the specific properties of the treatment agents (PAC, aluminum sulfate, anthracite, activated carbon), and the potential interactions with organic matter. The aim was to explain the mechanisms driving the mobility, enrichment, or depletion of elements during oil-polluted groundwater remediation.

3. RESULTS

3.1. Preliminary Analyses

The preliminary analyses of the groundwater samples revealed several key characteristics of the raw water and the initial effects of the treatment processes. The chemical composition of the groundwater, including both major and trace elements, was meticulously determined. Notably, according to the usual standard limits set by the World Health Organization (WHO) for drinking water [12, 13], the water samples from this study generally did not pose immediate concerns regarding the quality of either major or trace elements prior to treatment. This suggests that while oil contamination was present, the concentrations of many other constituents were within acceptable ranges, setting a baseline for the

impact of the remediation process.

Regarding the fundamental physicochemical parameters, pH exhibited only minor modifications across the different steps of the treatment, indicating that the remediation processes did not induce significant changes in the water's acidity or alkalinity. Similarly, electrical conductivity (EC) remained largely stable, suggesting that the total dissolved solids (TDS) content did not fluctuate substantially throughout the treatment train. These observations are crucial as pH and EC are significant controls on the speciation and mobility of many elements, and their stability simplifies the interpretation of observed changes in elemental concentrations to the direct effects of the treatment agents and processes.

The chemical composition of the raw groundwater indicated that the most abundant major elements present were Sodium (Na), Magnesium (Mg), Calcium (Ca), and Potassium (K). Among the trace elements, Zinc (Zn), Barium (Ba), Copper (Cu), and Nickel (Ni) were found to be the most abundant. This initial characterization of the groundwater provides a crucial reference point for understanding the subsequent changes induced by the ex-situ treatment. Interestingly, the chemical evolution of major elements throughout the various remediation steps did not reveal any significant modification, suggesting their relative insensitivity to the physical and chemical processes employed, unlike certain trace elements that exhibited dynamic behavior.

3.2. Main Findings

The investigations into the variations of trace elements during each step of the treatment process revealed diverse behaviors, providing critical insights into their mobility and the effectiveness of the ex-situ remediation. The following outlines the main findings regarding elemental changes relative to untreated water and through successive treatment stages.

Changes Relative to Untreated Groundwater:

Overall, when comparing the final treated water to the raw, untreated groundwater, a distinct pattern of elemental mobility emerged:

- Increased Elements: Aluminum (Al) and Zinc (Zn) concentrations increased relative to untreated groundwater. The increase in Al is particularly notable and is directly attributable to the addition of aluminum-based coagulants, specifically polyaluminum chloride (PAC) and an anion polymer (aluminum sulfate), to the raw water prior to the air flotation step. These chemicals are introduced to facilitate the coagulation of oil droplets, but their aluminum content inevitably contributes to the dissolved aluminum concentration in the treated water. The increase in Zn is a complex finding that suggests either release from organic complexes during oil removal or interaction with the filter media.

- Decreased Elements: The total concentration of Rare Earth Elements (REEs), Silver (Ag), Barium (Ba), Lead (Pb), Cadmium (Cd), and Nickel (Ni) generally decreased relative to the raw water after the entire treatment process. This reduction signifies the successful removal of these elements by the successive remediation steps, primarily through adsorption and physical filtration.

- Unchanged Elements: Major elements such as

Calcium (Ca), Chromium (Cr), Potassium (K), Magnesium (Mg), Sodium (Na), and Strontium (Sr) consistently remained unchanged throughout the treatment process. This confirms the earlier preliminary analysis that major ions are largely unaffected by the remediation techniques applied, suggesting that the treatment is highly specific to certain contaminants and trace elements rather than altering the bulk water chemistry.

Step-Wise Elemental Behavior:

A more granular analysis of elemental concentrations at each distinct stage of the ex-situ treatment process provided further detail:

After Air Flotation (Step 1, relative to raw water):

- Enriched Elements: Aluminum (Al), Nickel (Ni), Lead (Pb), and Manganese (Mn) concentrations showed significant enrichment after the air flotation step. Al increased by approximately 87% due to the addition of coagulants. Ni increased by about 47%, Pb by 21%, and Mn by 18%. This initial increase for some trace metals could be attributed to the disruption of oil-water emulsions, potentially releasing complexed metals, or interactions with the added coagulants.

- Depleted Elements: Silver (Ag) and the total Rare Earth Elements (REEs) experienced depletion, with approximately 228% and 39% decrease, respectively. This suggests that air flotation, along with the coagulation process, is effective in removing a portion of these elements, likely through co-precipitation or adsorption onto flocculated oil and suspended particles.

- Unchanged Elements: Barium (Ba) and Chromium (Cr) remained largely unchanged after the air flotation step.

After Anthracite Filtration (Step 2, relative to air flotation water):

- Enriched Elements: Water collected after filtration through anthracite showed enrichment in Cadmium (Cd), Rare Earth Elements (REEs), and Nickel (Ni), with increases of approximately 64%, 29%, and 25% respectively, relative to the water after air flotation. The increase in these trace elements after anthracite filtration is a significant finding and suggests that either a large fraction of these elements in the groundwater were carried by organic molecules that were subsequently released during filtration, or there was a release of these elements directly from the anthracite filter media itself. The evaporation of organic compounds and their retention on filters could potentially release associated trace elements, explaining the observed peaks, particularly for Cd and Ni.

- Depleted Elements: Conversely, Silver (Ag), Aluminum (Al), and Lead (Pb) were depleted after anthracite filtration, decreasing by approximately 250%, 34%, and 16% respectively. The decrease in Al is expected as the anthracite filter begins to remove the coagulant-metal complexes formed in the previous step.

- Unchanged Elements: Similar to the previous stage, Barium (Ba) and Chromium (Cr) concentrations remained unchanged.

After Activated Carbon Adsorption (Step 3, relative to anthracite filtered water):

- Enriched Elements: The final step, activated carbon adsorption, resulted in enrichment of Zinc (Zn), Silver (Ag), and Chromium (Cr) by approximately 96%, 71%, and 16% respectively, relative to the water after anthracite filtration. The increase in Zn, Ag, and Cr after activated carbon suggests complex interactions, possibly related to desorption phenomena or unique affinities with the carbon matrix under specific conditions.

- Depleted Elements: Cadmium (Cd) and Nickel (Ni) experienced significant depletion, with approximately 100% and 20% decrease respectively. Critically, the total concentration of Rare Earth Elements (REEs) was significantly depleted (more than 100% reduction) during this final step. This substantial decrease in REEs and other trace elements (Cd, Ni) after activated carbon treatment is primarily attributed to their effective retention and adsorption onto the porous activated carbon surface [11].

- Unchanged Elements: The concentrations of other elements did not exhibit any significant change after the removal of oil from the waters [21, 22].

3.3. Secondary or Exploratory Findings

Beyond the primary focus on individual trace element mobility, the study also yielded several important secondary or exploratory findings, particularly concerning the behavior of rare earth elements (REEs) and the overall water quality relative to drinking water standards.

Rare Earth Element (REE) Distribution Patterns:

The average total content of REEs in groundwater collected from the different monitoring wells was approximately 11.36 ppb. The total REE content in the untreated groundwater (raw water entering the plant) was about 15.85 ppb. This content subsequently decreased significantly from initial treatment (air flotation) to final adsorption (activated carbon), reaching as low as 0.37 ppb in the final treated water. This substantial depletion confirms the effectiveness of the multi-step treatment process in removing REEs from the polluted groundwater.

Crucially, the normalization of REE concentrations in waters collected after initial treatment (air flotation) and final adsorption (activated carbon) to the REE concentrations in the raw water before any treatment exhibited relatively flat patterns. This observation, where the ratios between REEs in samples and those in raw water were consistently less than 1 for all REEs after air flotation and activated carbon, suggests that there was no significant fractionation of REEs during these treatment steps. This implies that REEs were removed in a bulk manner, without preferential removal of light or heavy REEs, indicating that the primary removal mechanisms (e.g., adsorption, co-precipitation) did not differentiate based on individual REE properties.

However, the distribution patterns of REEs in groundwater after anthracite filtration showed a slight enrichment in heavy REEs (HREEs: Gd to Lu), accompanied by a slight positive anomaly in Cerium (Ce) and a slight negative anomaly in Europium (Eu). The ratio between REEs in samples and those in raw water was approximately 1 for light and intermediate REEs, but higher than 1 for HREEs during this stage. This subtle fractionation, alongside the Ce and Eu anomalies, might suggest more complex interactions with the anthracite media, potentially involving redox processes (for Ce and Eu) or differential adsorption capacities for HREEs. The normalization of REE distribution in waters treated during the remediation steps to an average distribution in groundwater also consistently showed flat patterns, further supporting the general lack of significant fractionation during the overall process. The release of REEs observed at the final step of treatment, though less significant than initial steps, may be attributed to the fixation of organic molecules on activated carbon, as the complexation of REEs with organic molecules in groundwater is known to be influenced by factors such as pH, alkalinity, and dissolved organic carbon concentration [21, 22, 23].

Comparison with Uncontaminated Groundwater:

A comparison of the contaminated groundwater in this study with uncontaminated groundwater from the same area, based on previous research [14], revealed that the oil-contaminated groundwater was characterized by lower concentrations of both major and trace elements. This suggests that the presence of oil or associated processes might inherently reduce the baseline concentrations of some elements, or that the uncontaminated reference represents different hydrogeochemical conditions.

Implications for Aluminum (Al) Concentration:

An important observation was the sustained increase in Aluminum (Al) concentration throughout the treatment process, particularly after the final step relative to raw water. This enrichment of Al is primarily attributed to the systematic addition of aluminum-based agents, such as polyaluminum chloride (PAC) and the anion polymer (aluminum sulfate), to the groundwater before remediation. These coagulants are essential for aggregating oil droplets, but they introduce aluminum into the water. Despite this increase, the final concentration of Al in the treated water remained below the permissible concentration for aluminum in drinking water standards [12, 13].

4. DISCUSSION

4.1. Interpretation of Key Findings

The results of this study provide a detailed understanding of the dynamic mobility of trace elements during the multi-step ex-situ remediation of oil-polluted groundwater in the Al Batinah region of Northeast Oman. The observed patterns of enrichment, depletion, and stability for various elements offer critical insights into the underlying mechanisms governing their fate during the treatment process.

The overall increase in aluminum (Al) concentration from the raw water through the successive treatment steps, particularly after the addition of coagulants, is a straightforward yet significant finding. Polyaluminum chloride (PAC) and aluminum sulfate, being aluminum-based, directly contribute dissolved Al to the water phase, even as they facilitate the removal of oil and other particulates. This highlights a common trade-off in water treatment: the introduction of one chemical to solve a specific problem can alter the concentrations of other elements. While the final Al levels remained within drinking water standards, continuous monitoring of such introduced chemicals and their potential long-term effects is warranted.

The contrasting behaviors of trace elements such as Ni, Zn, and Cu, which showed an initial increase after air flotation or anthracite filtration, versus Ag and total REEs, which generally decreased, reflect the complex interplay between physical, chemical, and biological processes during remediation. The initial increase in certain trace metals like Ni, Zn, Cu, and Mn after air flotation suggests that the coagulation and aeration process might actively release these elements from existing oil-water complexes or organic associations. Oil, being a complex mixture of hydrocarbons, often contains associated metals. The physical disruption during air flotation, coupled with the chemical action of coagulants, could break down these complexes, thereby mobilizing the metals into the aqueous phase. This phenomenon aligns with the understanding that trace elements can be complexed by dissolved organic matter, and their speciation is influenced by environmental conditions [15, 16, 17, 18, 19, 20, 21]. If the oil or associated organic matter was effectively removed, these elements could be liberated.

The subsequent increases in Cd, REEs, and Ni after anthracite filtration, relative to the air-floated water, are particularly intriguing. This could be indicative of desorption from the anthracite filter medium itself, or, as hypothesized in the results, a significant fraction of these trace elements might be carried by organic molecules that are released during the filtration process. Anthracite, with its functional groups, has a high affinity for natural organic matter [9]. As this organic matter is retained or altered on the filter, any associated trace elements could become desorbed back into the water. The observation that the evaporation of organic compounds and their retention on filters could lead to an "effect of concentration" and explain peaks like that of Cd and Ni reinforces the critical role of organic-metal interactions.

Conversely, the general decrease in Ag and total REEs, especially after activated carbon adsorption, points to effective removal mechanisms by these filtration stages. Activated carbon's high porosity and large surface area make it an excellent adsorbent for a wide range of contaminants, including many trace elements and organic compounds [11]. The significant depletion of total REEs (over 100% reduction after activated carbon) is a strong indicator of the activated carbon's efficiency in capturing these elements, likely through surface adsorption or complexation with residual organic matter bound to the carbon [21, 22, 23]. This is consistent with activated carbon's known capacity to retain various organic and inorganic species [11].

The remarkable stability of major elements (Na, Mg, Ca, K, Sr) and certain trace elements (Cr, Pb, Cd overall) throughout the entire treatment train suggests that these elements are either present in forms not significantly affected by the physical and chemical processes (coagulation, flotation, filtration) or are not readily mobilized or adsorbed under the prevailing conditions. Their stability simplifies the interpretation of changes in other, more mobile, trace elements.

4.2. Comparison with Previous Literature

The findings of this study resonate with and build upon a substantial body of existing literature on water pollution and remediation, while also providing unique insights pertinent to multi-step ex-situ treatments.

The initial observation that groundwater is a primary source of water in arid regions and the necessity for monitoring to prevent contamination and depletion aligns with broader discussions on water security and resource management, particularly in water-stressed areas globally [1]. The acknowledgment of industrial and anthropogenic sources as contributors to groundwater contamination is also well-documented in various studies addressing pollution risks [2, 3].

The application of air sparging as a remediation technique for oil contamination is consistent with its established use as a fast, clean, and economical method for treating volatile organic compounds and petroleum hydrocarbons in groundwater [8, 10]. Physical modeling studies have indeed contributed to optimizing air sparging applications [8], reinforcing the scientific basis for its inclusion as a preliminary step in this ex-situ treatment.

The effectiveness of activated carbon (AC) filtration in reducing various organic compounds, chlorine, and certain heavy metals like lead and dissolved radon from drinking water, as reported by Dvorak and Skipton [11], is strongly supported by our findings, especially the significant depletion of total REEs, Cd, and Ni after the activated carbon adsorption step. The role of anthracite as a filter medium, particularly for natural organic matter due to its surface functional groups [9], also finds resonance, especially when considering the potential for desorption of elements associated with organic matter during this stage. The comprehensive reviews on groundwater contamination and remediation, encompassing occurrence, migration, and adsorption modeling [10], provide a broad context for our detailed investigation into elemental mobility.

The observed complex interactions between trace elements and dissolved organic matter (DOM) are a critical aspect of environmental geochemistry, a topic extensively investigated in the literature [15, 16, 17]. Petersen [15] highlighted the contradictory biological behavior of humic substances in aquatic environments, which are a major component of DOM, underscoring the complexity of their interactions with metals. Alberic et al. [16] demonstrated the interactions between trace elements and DOM in anoxic deep layers of lakes, showing how DOM influences their speciation. Similarly, Boren and Grimvall [17] provided a broader context on humic substances in both aquatic and terrestrial environments. Our study's findings, where the removal or alteration of organic components during oil remediation led to changes in trace element concentrations (e.g., release of Ni, Zn, Cu), reinforce the established role of DOM as a carrier and complexing agent for metals [18, 19, 20]. Studies by Karlik and Szpakowska [18] on labile organic matter and heavy metals in agricultural landscapes, Hirata [19] on speciation of dissolved metals associated with organic matter in coastal seawaters, and Soltan et al. [20] on speciation in River Nile mud, all emphasize the importance of understanding these associations.

The specific behavior of rare earth elements (REEs) in this study, particularly their significant depletion during the treatment process without substantial fractionation, is noteworthy. While previous research, such as that by Johannesson et al. [22] on REE concentrations and speciation in organic-rich blackwaters, and Pourret et al. [23] on organic complexation of REEs in natural waters, has highlighted the influence of organic matter on REE mobility and speciation, our study adds to this by showing how a multi-stage ex-situ treatment process impacts their bulk removal and fractionation. The lack of significant fractionation observed in our study, despite the influence of organic molecules on REE complexation [21, 22, 23], suggests that the remediation mechanisms employed (coagulation, physical filtration, adsorption) are largely non-discriminatory regarding the individual properties of different REEs. Chukwujindu et al. [21] studied heavy metal speciation in crude oil impacted sediments, which provides a relevant context for understanding how metals might be released or behave in an oil-contaminated environment. The observed increase in aluminum (Al) due to the addition of aluminum-based coagulants is a well-known phenomenon in water treatment, where coagulants like PAC and aluminum sulfate are commonly used to remove suspended solids and organic matter, and thus contribute to the Al concentration in the treated water.

4.3. Strengths and Limitations of the Study

This study possesses several strengths that enhance the credibility and applicability of its findings:

- Comprehensive Multi-Stage Analysis: A significant strength is the detailed, step-by-step investigation of trace element mobility across an entire ex-situ treatment train. By collecting and analyzing samples from raw water to the final treated water, including intermediate stages (air flotation, anthracite filtration, activated carbon adsorption), the study provides a granular understanding of how each specific remediation step influences elemental concentrations. This level of detail is often lacking in broader assessments of water treatment efficiency.

- Broad Suite of Elements: The analysis included a wide range of major, trace, and rare earth elements. This comprehensive elemental screening allowed for the identification of diverse behavioral patterns, offering a more complete picture than studies focusing on only a few target contaminants. The inclusion of REEs, in particular, provided valuable insights into their collective and individual responses to the treatment, given their sensitivity as geochemical tracers.

- Real-World Application: The study was conducted on actual oil-polluted groundwater from a specific, affected area (Al Batinah region, Oman) and involved an operational ex-situ treatment plant. This lends a high degree of ecological validity to the findings, making them directly relevant to practical groundwater remediation efforts.

- Rigorous Analytical Methodology: The use of high-precision analytical techniques like ICP-AES and ICP-MS, coupled with a robust quality assurance/quality control (QA/QC) program (including calibration standards, blanks, and repeated analyses), ensures the reliability and accuracy of the elemental concentration data.

Despite these strengths, the study also has certain limitations:

- Lack of Speciation Data: While the study highlights the importance of speciation and infers certain mechanisms (e.g., release from organic complexes), direct measurements of trace element speciation at each stage were not performed. Understanding the specific chemical forms (e.g., free ions, organic complexes, particulate-bound) of the elements would provide a more definitive explanation for their observed mobility, particularly for elements showing unexpected increases or decreases. The recommendation for future studies to include speciation analysis underscores this limitation.

- Limited Characterization of Treatment Agents: The study acknowledges the introduction of chemical agents (PAC, aluminum sulfate) and filter media (anthracite, activated carbon). While their general roles are known, a more detailed chemical characterization of these agents (e.g., their trace element content, surface properties, and potential for leaching) would provide a clearer understanding of their direct contribution to changes in water chemistry.

- Absence of Mass Balance: A comprehensive mass balance analysis for each element across the entire treatment train was not explicitly presented. Such an analysis would quantify the exact amount of each element removed or retained by each step, providing a more robust measure of overall efficiency and identifying any unaccounted-for fractions.

- Snapshot in Time: The study represents a snapshot of the treatment process. Long-term monitoring and analysis would be beneficial to assess the sustainability of the treatment and identify any potential long-term changes in filter media performance or elemental mobility.

- Generalizability: While offering valuable insights, the findings are specific to the hydrogeochemical conditions and oil contamination characteristics of the Al Batinah region and the specific treatment plant design. Extrapolating these results directly to other sites with different pollution types, geological settings, or treatment configurations should be done with caution.

4.4. Implications for Theory and Practice

The findings of this study have significant implications for both theoretical understanding and practical applications in environmental science and water resource management, particularly concerning contaminated groundwater remediation.

Theoretical Implications:

- Complex Interactions of Trace Elements: The study underscores the highly complex and dynamic interactions of trace elements within multi-stage remediation systems. The observed enrichments of certain elements (Ni, Zn, Cu, Al) at specific stages, followed by depletions at others, challenge simplistic views of contaminant removal. It suggests that remediation processes do not merely remove pollutants but actively transform the chemical matrix, potentially leading to the mobilization of previously bound elements. This highlights the need for theoretical models that account for these nuanced, multi-faceted geochemical reactions occurring at each treatment interface.

- Role of Organic Matter and Coagulants: The inferred role of dissolved organic matter (DOM) in complexing trace elements and the impact of its removal (or the addition of coagulants to facilitate oil/organic removal) on metal mobility is a critical theoretical point. The study implies that processes designed to remove bulk organic contaminants can inadvertently liberate associated trace metals, emphasizing the need for a more integrated understanding of organic-inorganic pollutant dynamics. The increase in aluminum due to coagulant addition also highlights the need for theoretical frameworks that consider the entire chemical footprint of remediation agents.

- REE Behavior in Anthropogenic Systems: The consistent, non-fractionated depletion of REEs, particularly by activated carbon, adds to the theoretical understanding of REE geochemistry in anthropogenically impacted and remediated systems. While REEs are often used as geochemical tracers sensitive to redox and pH conditions, their bulk removal without significant fractionation in this treatment suggests that physical adsorption and co-precipitation mechanisms dominate over differential chemical reactions in this context. This informs models predicting REE fate in engineered environments.

Practical Implications:

● Holistic Treatment Design: For practitioners, the study emphasizes the necessity of a holistic approach to designing groundwater remediation systems. Focusing solely on the removal of primary contaminants (e.g., oil) without considering the broader suite of trace elements can lead to unintended consequences, such as the mobilization or re-release of other regulated contaminants. A detailed chemical assessment at each treatment stage, rather than just pre- and post-treatment, is crucial for optimizing overall performance.

● Careful Selection and Monitoring of Chemical Agents: The observed increase in aluminum due to coagulant addition highlights the practical need for careful selection and precise dosing of chemical agents in water treatment. While effective for coagulation, their residual impact on water chemistry must be monitored to ensure compliance with drinking water standards and avoid introducing new contaminants. This necessitates robust monitoring protocols for all inputs to the treatment process.

● Importance of Speciation Studies for Optimization: The study strongly recommends that future remediation efforts include detailed speciation analyses of key trace elements [21, 22, 23]. From a practical standpoint, understanding the specific chemical forms of metals (e.g., ionic, complexed, colloidal) would allow for the design of more targeted and efficient removal strategies. For instance, if a metal is primarily organically complexed, a treatment focusing on organic matter removal would be highly effective. If it's particulate-bound, filtration would be key. This granular understanding can lead to more cost-effective and environmentally sound solutions.

● Enhanced Monitoring for Complex Contaminants: The study's findings, particularly the complex behavior of trace elements like Zn, Ag, and Cr throughout the activated carbon stage, underscore the need for enhanced and continuous monitoring of treated water. Even after conventional treatment, unexpected increases or re-mobilization of certain elements can occur, necessitating vigilant quality control to ensure that the water meets all regulatory requirements for its intended use, especially drinking water.

● Research Direction for Filter Media: The observed enrichment of some elements (Cd, REEs, Ni) after anthracite filtration points to a practical research direction: further investigation into the potential for desorption or leaching from filter media under changing chemical conditions. This could lead to the development of novel filter materials with improved retention properties or strategies to regenerate media more effectively without re-mobilizing contaminants.

4.5. Conclusion and Future Research Directions

This comprehensive study meticulously investigated the mobility of trace elements during a multi-step ex-situ remediation process for oil-polluted groundwater in the Al Batinah region, Northeast Oman. The findings demonstrate that while the treatment effectively reduces oil contamination, the behavior of various trace elements is highly dynamic and complex, with some showing unexpected increases at certain stages and others consistent depletion. Notably, aluminum concentrations increased due to coagulant addition, while elements like Ni, Zn, and Cu showed initial enrichments, and Ag and total REEs generally decreased across the treatment train. Major elements and several trace elements (Cr, Pb, Cd) largely remained stable. Crucially, the rare earth elements were significantly depleted by the final activated carbon step, and their distribution patterns did not reveal any significant fractionation, suggesting bulk removal mechanisms.

Based on these findings, the study concludes that a thorough, stage-by-stage chemical assessment is indispensable for optimizing groundwater remediation strategies. Understanding the intricate interactions between contaminants, treatment agents, and various elements is key to achieving effective decontamination and ensuring water quality.

For future research, the following directions are recommended:

● Detailed Speciation Studies: Future investigations should incorporate direct measurements of trace element speciation at each stage of the treatment process. This would provide definitive evidence for the chemical forms of the elements and explain their observed mobility more precisely.

● Long-Term Performance Assessment: Longitudinal studies are needed to assess the long-term performance and sustainability of ex-situ treatment plants. This includes monitoring the aging of filter media and their potential for desorption or reduced efficiency over extended periods.

● Mechanism of Desorption and Mobilization: Further research should specifically focus on the mechanisms driving the observed increases in certain trace elements (e.g., Cd, Ni, Zn) after specific filtration steps. This could involve controlled laboratory experiments to simulate the conditions and identify the precise factors leading to their mobilization.

● Characterization of Organic-Metal Interactions: A deeper understanding of the complexation between dissolved organic matter and trace elements, particularly REEs, throughout the remediation process, would be beneficial. This could involve advanced analytical techniques to characterize changes in DOM composition and its binding capacity.

- Pilot-Scale and Field Validation: While this study was conducted on an operational plant, further pilot-scale experiments and broader field validations across different hydrogeological settings would strengthen the generalizability of the findings and refine treatment protocols.

These research directions will contribute to the development of more robust, efficient, and environmentally sound groundwater remediation technologies for oil-polluted aquifers in arid regions and beyond.

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