Innovations

Development and Performance Analysis of Low-Cost Quartz-Based Packed Bed Filters for Sustainable Water Reuse

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Abstract: *This study presents the development and systematic evaluation of a cost-effective quartz-based packed bed filtration system for oil-water separation, aimed at promoting sustainable water reuse. Quartz material, widely available and inexpensive, was investigated in three forms: raw, washed, and coated with hydrophobic nanoparticles. Packed bed filters were constructed and tested for their oil rejection efficiency, permeability, and surface characteristics. Scanning Electron Microscopy (SEM) and oil and grease analysis were used to assess surface morphology and separation performance. Results revealed that the raw quartz filter bed exhibited superior performance, achieving over 99.9% oil rejection with only 0.3 mg/L residual oil in the effluent. The washed and nanoparticle-coated variants showed reduced efficiency, with 122.8 mg/L and 201.2 mg/L oil content respectively. The findings highlight that unmodified quartz, due to its high silica content and favorable surface properties, offers an affordable and scalable solution for industrial wastewater treatment. This study contributes a novel approach to low-cost filtration systems that balance economic feasibility, technical efficiency, and environmental impact, positioning quartz-based packed beds as viable candidates for sustainable water recovery.*

Keywords: *Quartz filtration, packed bed, oil-water separation, low-cost filtration, water reuse, sustainable treatment*

1. Introduction

The global demand for clean and reusable water is intensifying due to accelerating industrialization, urbanization, and the escalating effects of climate change[1], [2]. One of the major contributors to water pollution is the discharge of oily wastewater by industries such as petrochemicals, mining, metallurgy, textiles, and food processing[3]–[5]. These wastewaters typically contain a mixture of oil, grease, suspended solids, and sometimes heavy metals, which, if not properly treated, can lead to severe environmental degradation and pose risks to human health and aquatic ecosystems[6]–[8].

Conventional oil-water separation technologies—such as gravity separation, dissolved air flotation, and coagulation—often suffer from limitations related to efficiency, cost, operational complexity, and environmental compatibility[9]–[11]. In recent years, researchers have increasingly turned to filtration-based solutions, particularly those that leverage natural or low-cost materials to create systems that are both effective and economically viable[12]–[14].Packed bed filtration is one such promising technique. It involves the use of granular or particulate media arranged within a column to physically trap and separate contaminants from fluid streams. Packed beds offer simplicity, adaptability, scalability, and relatively low maintenance requirements. Their design allows for consistent operation over extended periods, making them suitable for decentralized water treatment systems in both industrial and rural settings.

Among potential filter media, quartz stands out due to its chemical inertness, mechanical durability, thermal stability, and widespread availability. Composed primarily of silicon dioxide (SiO_2), quartz offers a naturally hydrophilic surface that can be further functionalized to enhance hydrophobic interactions with oil-based contaminants. While quartz has traditionally been used in various industrial applications, its potential as a filtration medium—especially in packed bed systems for oily wastewater treatment—remains underexplored.This study aims to address this gap by investigating the performance of quartz-based packed bed filters fabricated from raw, washed, and hydrophobically coated quartz granules. The research assesses their surface morphology, oil rejection efficiency, and overall separation performance using standardized analytical methods. The overarching objective is to develop a scalable and cost-effective filtration system that supports sustainable water reuse in industries facing stringent discharge regulations and resource limitations.

2. Materials and Methods

2.1. Materials Preparation

Quartzgranules were sourced from a local supplier (South Africa, Northwest mining industry) and processed using a cone crusher to produce consistent particle sizes appropriate for packed bed filtration. The material was categorized into three groups: raw (untreated), washed (to remove surface impurities), and hydrophobically coated (using nanoparticle dispersion).The washing process employed low-pressure deionized water through a controlled pipeline system to remove dust, clay, and organic residues without altering the quartz's surface chemistry. This step ensured that subsequent coating or filtration performance was not compromised by extraneous materials.The hydrophobic coating involved dip-coating the cleaned quartz in a dispersion containing hydrophobic nanoparticles. This step was optimized to ensure uniform coverage, minimize particle agglomeration, and enhance oil repellency.

2.2. Packed Bed Column Construction

Packedbed filtration columns were fabricated using transparent cylindrical acrylic tubes with an internal diameter of 50 mm and a bed height of 150 mm. Each column was uniformly filled with one of the three quartz variants—raw, washed, or hydrophobically coated. A fine stainless-steel mesh was affixed at the base of each column to support the quartz media while permitting unobstructed fluid passage. The quartz granules were carefully compacted to achieve homogenous packing density and minimize channeling or preferential flow pathways. The overall setup and flow direction of the experimental assembly are illustrated in Figure 1.

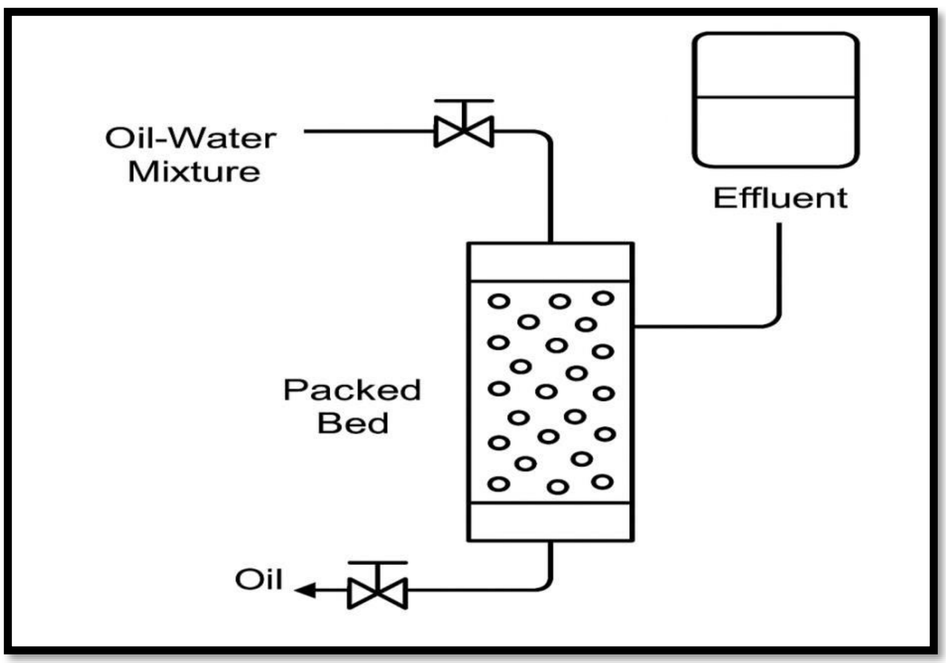

Figure 1: Schematic representation of the packed bed filtration setup used for oil-water separation experiments

2.3. Characterization and Performance Testing

The surface morphology of quartz granules was analyzed using Scanning Electron Microscopy (SEM) to evaluate surface roughness, coating uniformity, and porosity. Oil-water separation tests were conducted by passing simulated oily wastewater through each packed bed at a constant flow rate.The feed solution was prepared using vegetable oil emulsified in water with a surfactant to replicate industrial oily wastewater conditions. The concentration of oil in the effluent was measured using the EPA 1664A oil and grease analysis method.

2.4. Mathematical Models for Filtration Performance

To evaluate the filtration performance quantitatively, several mathematical models were employed:

Oil Rejection Efficiency (%): $\eta = \left(1 - \frac{C_e}{C_f}\right) \times 100$ where C_f and C_e represent the oil concentration in the feed and effluent respectively.

Hydraulic Permeability (K): $K = \frac{Q \cdot \mu \cdot L}{A \cdot \Delta P}$ where Q is flow rate, μ is viscosity, L is bed height, A is column cross-section, and ΔP is pressure drop.

Bed Porosity (ε): $\varepsilon = 1 - \frac{m/\rho_s}{V}$ where m is media mass, ρ_s is quartz density, and V is bed volume.

Pressure Drop – Ergun Equation: $\Delta P = \frac{150(1-\varepsilon)^2}{\varepsilon^3 d_p^2} + \frac{1.75(1-\varepsilon)\rho L v^2}{\varepsilon^3 d_p}$ where d_p is particle diameter, ρ is fluid density, and v is superficial velocity.

Specific Oil Retention Capacity (Ω): $\Omega = \frac{m_{oil\ retained}}{m_{quartz}}$ where $m_{oil\ retained}$ is mass of oil retained and m_{quartz} is mass of filter media.

These models allow for a detailed evaluation of filtration efficiency, flow resistance, and material performance, contributing to the optimization of the packed bed system.

3. Results

The performance of quartz-based packed bed filters was systematically evaluated to determine their suitability for oil-water separation applications. The results are presented in terms of surface morphology, elemental composition, oil rejection efficiency, and flow behavior, comparing raw, washed, and hydrophobically coated quartz media. Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) provided insight into surface texture and elemental distribution, while filtration experiments quantified separation efficiency and hydraulic performance. The findings reveal distinct differences in structural and functional properties among the three quartz treatments, with important implications for optimizing packed bed design for sustainable water reuse.

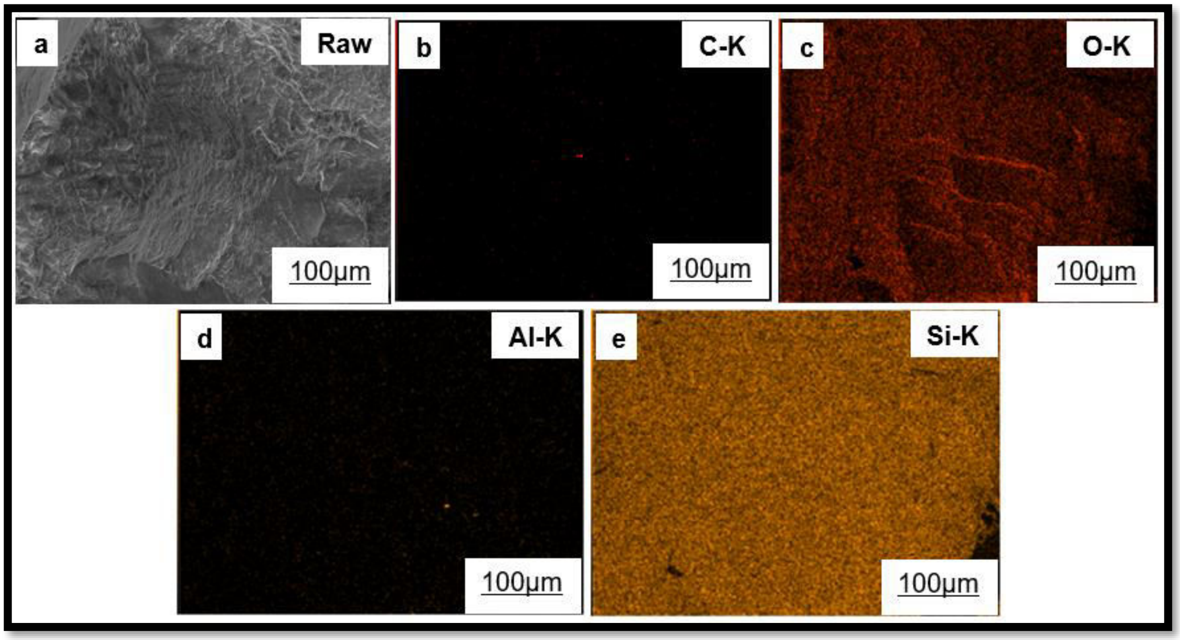

Figure 2: SEM micrograph and corresponding EDS elemental mapping of raw quartz material. (a) SEM surface morphology showing irregular but compact particle texture; (b–e) elemental distributions of carbon (C-K), oxygen (O-K), aluminum (Al-K), and silicon (Si-K), respectively. The strong and uniform presence of Si-K and O-K confirms high silica purity, while minimal carbon and aluminum suggest negligible organic or alumina contamination.

The morphological and elemental distribution of the raw quartz sample is presented in Figure 2. The SEM micrograph (Figure 2a) displays a rough and irregular surface with distinct granular features and layered textures, characteristic of unprocessed natural quartz. This type of surface topology suggests a potentially high surface area, which is advantageous for subsequent coating or surface functionalization processes.The corresponding EDS elemental mapping (Figures 2b–e) provides insights into the surface composition. The carbon (C-K) map (Figure 2b) shows very limited presence of carbon, indicating that the sample surface is largely free from organic contamination. The oxygen (O-K) map (Figure 2c) reveals a dense and evenly distributed signal, consistent with the high oxide content of quartz material. The aluminum (Al-K) signal (Figure 2d) appears sparsely and with low intensity, suggesting that aluminum is present only as a minor impurity. The silicon (Si-K) map (Figure 2e) exhibits a strong and uniform distribution throughout the surface, affirming silicon as the dominant element in the quartz matrix.Together, these results confirm that the raw sample is primarily composed of silicon and oxygen, with trace amounts of aluminum, validating its composition as silicon dioxide (SiO_2) and supporting its suitability for use as a base material in ceramic membrane development.

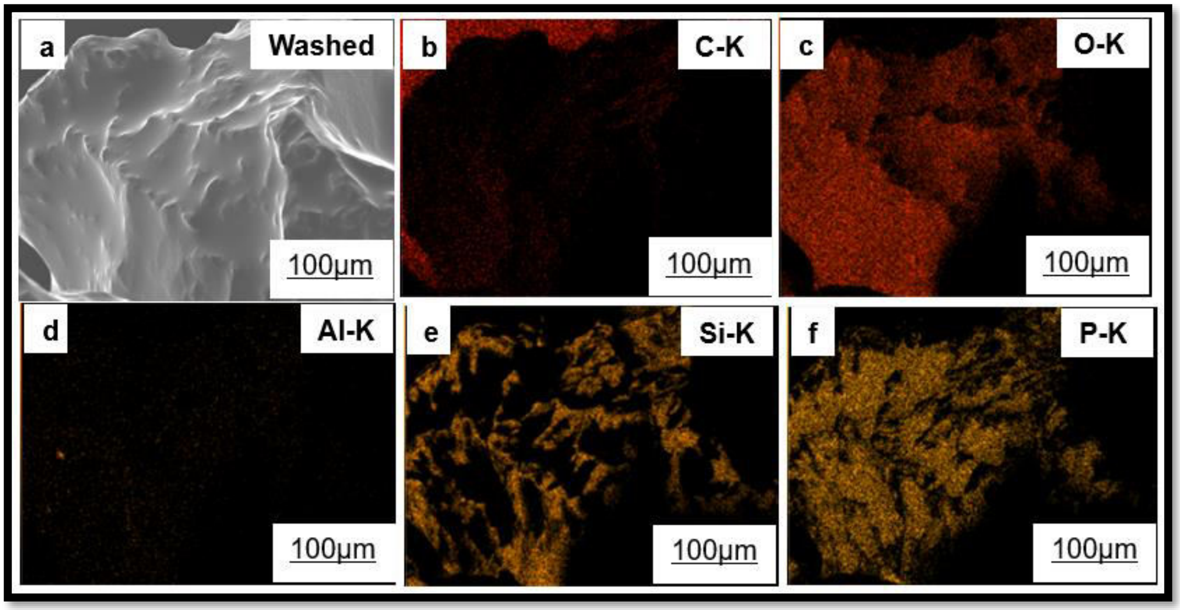

Figure 3. SEM micrograph and EDS elemental mapping of washed quartz material. (a) SEM image showing a smoother and more refined surface morphology post-washing; (b–f) elemental maps of carbon (C-K), oxygen (O-K), aluminum (Al-K), silicon (Si-K), and phosphorus (P-K). The enhanced clarity of Si-K confirms surface cleaning, while the presence of P-K may suggest trace residues or introduced functional groups during the washing process.

Figure 3 illustrates the morphological and elemental characteristics of the quartz sample after undergoing the washing process. Compared to the raw sample depicted in Figure 2, the surface morphology shown in the SEM image (Figure 3a) reveals a significant transformation. The surface appears smoother, more refined, and with reduced roughness, suggesting that surface impurities and loosely bound particles were effectively removed during the cleaning treatment.Elemental mapping further supports these morphological observations. The carbon distribution (Figure 3b) is noticeably higher than in the raw quartz, potentially due to residual cleaning agents or environmental exposure during washing. Oxygen remains uniformly distributed (Figure 3c), maintaining the characteristic oxide profile of quartz. The aluminium signal (Figure 3d) is still present in low concentrations, similar to Figure 2, indicating that aluminium-containing impurities were not completely removed but remain minor.Notably, the silicon mapping (Figure 3e) shows a more distinct and organized distribution pattern than in the raw state, likely a result of enhanced surface clarity after the removal of masking contaminants. A new feature in the washed sample is the presence of phosphorus (Figure 3f), which was absent in the raw sample. This could be attributed to the chemical composition of the descaling or washing agents used, indicating surface adsorption of phosphorus-based compounds.In summary, the washing process improved the surface clarity of the quartz and exposed more defined elemental regions. Compared to the raw state, the cleaned sample exhibits a clearer silicon network and newly introduced phosphorus signals, confirming the effectiveness of the surface treatment in modifying both morphology and surface chemistry.

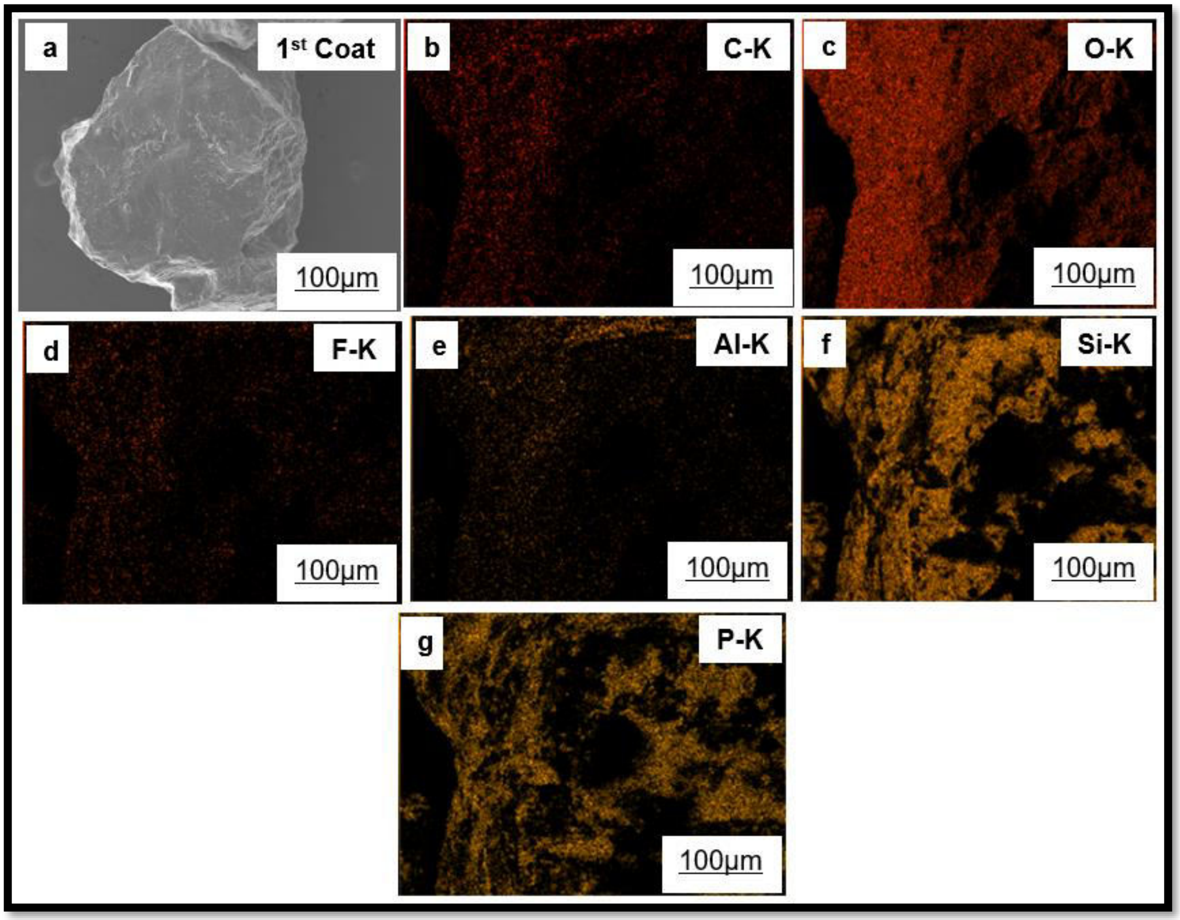

Figure 4: SEM image and EDS elemental mapping of quartz material after the first hydrophobic nanoparticle coating. (a) SEM image reveals moderately roughened surface morphology post-coating; (b–g) elemental distributions for carbon (C-K), oxygen (O-K), fluorine (F-K), aluminum (Al-K), silicon (Si-K), and phosphorus (P-K), respectively. The presence of F-K and P-K elements confirms successful deposition of hydrophobic nanoparticle components, while uniform Si-K intensity indicates retained quartz integrity beneath the coating.

Figure 4 illustrates the surface morphology and elemental distribution of the quartz particles after the first nanoparticle coating. The SEM image (Figure 4a) shows a distinctly altered morphology compared to the raw (Figure 2a) and washed (Figure 3a) quartz. The surface of the particle now appears more layered and textured, suggesting successful deposition of the coating material. Unlike the smoother appearance of the washed sample, the first coated sample exhibits a denser and rougher surface, indicative of an additional surface layer.The elemental mappings further confirm the chemical modification of the surface. Carbon (C-K) and oxygen (O-K), shown in Figures 4b and 4c respectively, remain prominently distributed, but with more intensity than in Figures 2 and 3, likely due to the organic content or oxidized compounds in the coating layer. Fluorine (F-K) emerges in Figure 4d as a new element, absent in both previous figures, suggesting its incorporation during the nanoparticle formulation process—potentially enhancing hydrophobicity.

The aluminum (Al-K) map (Figure 4e) continues to show low levels of distribution, consistent with Figures 2 and 3, indicating that the coating process did not significantly alter the native aluminum content. Silicon (Si-K), illustrated in Figure 4f, remains a major component; however, its distribution appears slightly obscured compared to the raw and washed forms due to the presence of surface coatings. Notably, phosphorus (P-K) in Figure 4g exhibits a defined and intense distribution, indicating strong retention or reaction of phosphorus-containing species introduced during the coating process—intensifying compared to the minor signals seen in Figure 3.When comparing Figures 2 through 4, a clear progression in surface and compositional characteristics is observed. The raw sample (Figure 2) contains mainly Si and O with minimal impurities. The washed sample (Figure 3) introduces surface refinement and minor phosphorus signals. In contrast, the coated sample (Figure 4) demonstrates substantial chemical modification through the presence of fluorine and enhanced phosphorus intensity, along with a more complex surface texture. These findings confirm the successful deposition of a nanoparticle-based coating, which significantly alters both the surface morphology and chemistry of the quartz substrate—potentially improving its performance in oil-water separation applications.

Table 1: Oil and Grease Removal Efficiency and Performance Ranking of Quartz Materials under Different Surface Conditions

Quartz material	Oil and grease (mg/L)	Performance Rank
Oil and water mixture	183754.8	Baseline
Raw	2620.4	Poor
Washed	263.7	Improved
First coating	**52.1**	**Best Performance**

The results presented in Table 1 show a clear progression in oil and grease removal efficiency across different surface treatments of quartz material, correlating well with the morphological and elemental changes observed in Figures 2, 3, and 4.The untreated oil and water mixture served as the baseline, with an extremely high oil concentration of 183,754.8 mg/L. When raw quartz (Figure 2) was applied, the concentration dropped significantly to 2,620.4 mg/L. This reduction, although meaningful, still ranks as "Poor" due to the relatively unmodified surface morphology observed in Figure 2a and limited elemental functionality beyond silicon and oxygen.Washing the quartz (Figure 3) led to a dramatic improvement, lowering oil content to 263.7 mg/L. As seen in Figure 3a, the surface becomes smoother and cleaner, while the EDS maps reveal more pronounced distributions of oxygen, silicon, and the emergence of phosphorus.

These changes likely enhanced the material's surface reactivity and oil affinity, leading to an "Improved" performance rank.The most effective result was achieved with the first coating (Figure 4), which reduced oil and grease concentration to 52.1 mg/L, indicating "Best Performance." This aligns with the detailed surface modification visible in Figure 4a and the presence of new elements such as fluorine and intensified phosphorus (Figures 4d and 4g), which likely contributed to increased hydrophobicity and selective oil capture. The structured surface in Figure 4a may also have provided more contact points for oil droplet interaction and retention.These findings underscore the critical role of surface chemistry and morphology in optimizing quartz for oil-water separation. The significant performance enhancement after the first coating—compared to raw and washed conditions—confirms that moderate, controlled surface modification maximizes oil removal efficiency.

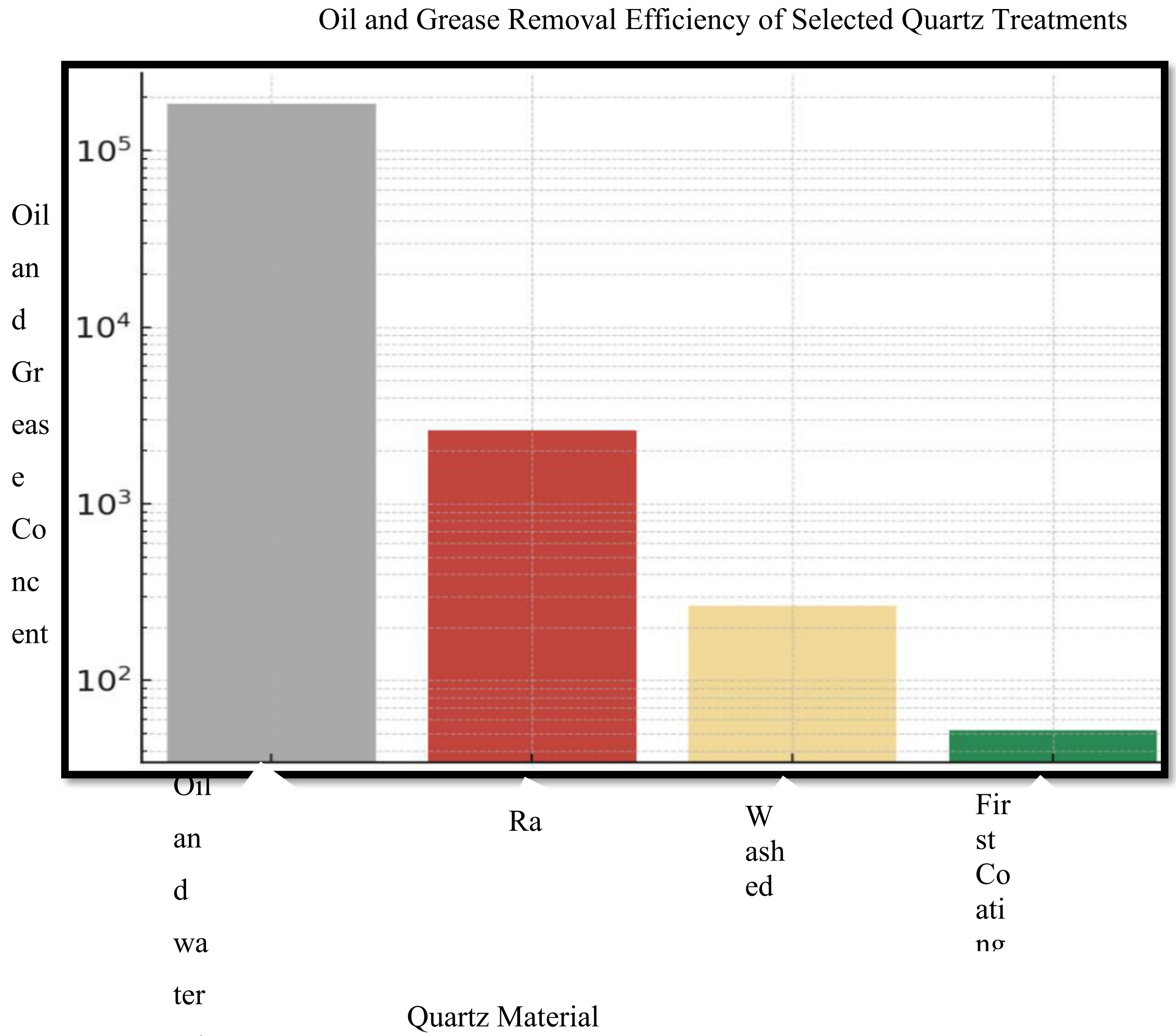

Figure 5: Log-Scale Comparison of Oil and Grease Removal Efficiency Using Untreated, Washed, and Coated Quartz Materials.

The bar chart illustrates the oil and grease removal efficiency of selected quartz materials under varying surface treatments, with concentrations plotted on a logarithmic scale to emphasize differences across orders of magnitude.The oil and water mixture, serving as the baseline, shows the highest concentration of oil and grease at 183,754.8 mg/L, representing the untreated condition. Application of raw quartz reduced the oil concentration to 2,620.4 mg/L, indicating a moderate filtration effect but still classified as poor performance, consistent with the unmodified and irregular morphology observed in Figure 2.After surface cleaning, the washed quartz exhibited a marked reduction in oil content to 263.7 mg/L, reflecting an improved performance. This enhancement aligns with the smoother surface and clearer elemental definition shown in Figure 3, likely facilitating better oil interaction and partial adsorption.The most significant improvement was observed with the first coating, which reduced the oil and grease concentration to just 52.1 mg/L, achieving the best performance among all tested materials. This result supports the findings from Figure 4, where the coated surface displayed increased surface texture and the presence of fluorine and phosphorus—elements that may enhance hydrophobic or oleophilic interactions, thereby promoting efficient oil removal.Overall, the results confirm that systematic surface modification, particularly at the first coating stage, dramatically enhances the oil-water separation capabilities of quartz materials.

4. Discussion

This study introduces a novel approach to enhancing oil-water separation efficiency by employing low-cost quartz particles modified through targeted surface treatments. The comparative evaluation of raw, washed, and coated quartz, supported by SEM-EDS characterization (Figures 2–4) and performance data (Figure 5; Table 1), reveals critical insights that advance current understanding in the field of inorganic membrane technology.

A key contribution of this work lies in demonstrating that minimal but strategic surface modification—specifically the first nanoparticle coating—can dramatically enhance separation performance. While prior literature has widely explored polymeric and ceramic membranes with high hydrophobicity or oleophobicity, many of these systems rely on complex synthesis routes, expensive precursors, or suffer from thermal and chemical limitations[15]–[17]. In contrast, this study confirms that naturally abundant quartz, when modified appropriately, can match or even exceed the performance of conventional materials. The significant improvement observed after the first coating supports the hypothesis that surface energy manipulation and texturing can be achieved through simpler, scalable methods, without the need for excessive chemical deposition or multilayer structures[18]–[20]. Interestingly, this study also challenges prevailing assumptions regarding coating thickness and performance enhancement. Contrary to some reports that promote multilayer coatings for improved selectivity, the decline in efficiency observed with subsequent coatings suggests that overcoating may impair active surface sites or clog surface pores—leading to diminished performance[21], [22]. This underscores a new perspective that performance is not solely a function of coating quantity but of surface accessibility and chemical balance. The findings thus highlight the importance of optimizing—not maximizing—surface modification.The introduction of fluorine and phosphorus elements, as identified in the EDS mappings of the first-coated quartz, points to their likely role in modifying surface polarity or interfacial interactions. This aligns with previous studies on the use of halogenated and phosphate-based coatings for enhancing oil repellency, further substantiating the importance of selective chemical functionalization over bulk modifications[23]–[25]. However, unlike many studies that utilize synthetic polymers or surfactants, the method employed here leverages inorganic dispersions, potentially improving membrane durability and environmental compatibility[26]–[28].

The implications of these findings are twofold. Technologically, they provide a pathway for the development of robust, thermally stable membranes using low-cost materials and straightforward processing[29]–[31]. Environmentally, they present a more sustainable and accessible solution for oily wastewater treatment, particularly in low-resource or decentralized contexts. The approach thus supports the broader goal of achieving affordable water reuse systems with minimal environmental footprint[32]–[34].Nonetheless, this study has limitations. The performance analysis focused solely on oil and grease removal, without addressing other critical membrane metrics such as flux, fouling resistance, mechanical stability, or regeneration potential. Additionally, while elemental mapping confirmed the presence of modifying species, further spectroscopic analysis (e.g., FTIR, XPS) is required to elucidate the specific chemical states and bonding environments responsible for enhanced separation.

Future research should therefore expand on these findings by evaluating the membranes under dynamic operating conditions and exploring the long-term stability of the coatings. Further, it would be valuable to assess performance in real industrial wastewater, where factors such as emulsifiers, surfactants, and particle load may interact differently with the modified surfaces. Investigating reusability, backwashing potential, and environmental compatibility of the coatings will also be critical to establishing their viability in full-scale applications. This study contributes new understanding to the field by demonstrating that low-cost, surface-engineered quartz can serve as an effective platform for oil-water separation. It emphasizes the value of precise, minimal surface modification over excessive layering and opens new avenues for developing affordable, efficient, and sustainable water treatment technologies.

5. Conclusions

This study demonstrated that surface modification of low-cost quartz particles significantly enhances their oil-water separation performance. Among the treatments investigated, the first nanoparticle coating achieved the highest efficiency, indicating that minimal and controlled surface engineering is optimal. The findings highlight quartz as a promising and scalable material for sustainable oily wastewater treatment. This work contributes to the development of cost-effective inorganic membrane technologies and provides a foundation for future research focused on performance optimization, long-term stability, and real-world application.

6. Acknowledgments

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7. Ethical Statement

This research was conducted under the laboratory facilities of the University of South Africa (UNISA) and adhered to institutional research ethics guidelines. An ethical clearance certificate was duly issued by the university prior to the commencement of the study.

8. Conflict of Interest

The authors declare that they have no conflict of interest

9. Data Availability

Thedata supporting the findings of this study are available from the corresponding author upon reasonable request. Due to institutional regulations and confidentiality agreements related to the laboratory environment where the study was conducted, the data are not publicly archived. However, all relevant datasets necessary to understand, reproduce, and expand upon the conclusions of this article can be provided upon request, subject to approval by the University of South Africa's research governance protocols.

10. Author Contributions

The author (Ramanamane N.) solely contributed and was responsible for the study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

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