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Microstructural performance of quartz-based pre-filtration devices for oil/water separation

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Abstract

Effective and affordable technologies are urgently needed for oily wastewater treatment, where conventional polymeric membranes suffer from fouling and ceramic membranes remain cost-prohibitive. This study investigates quartz particles (0.8–1.8 mm) as a low-cost pre-filtration medium for oil/water separation, focusing on the influence of raw versus acid-washed surfaces. Experiments using a packed quartz bed demonstrated that both media substantially reduced influent oil concentrations (initial 4393.80 mg/L), with raw quartz achieving 98.07% removal and washed quartz further improving efficiency to 98.48%. Surface cleaning enhanced quartz performance by eliminating impurities, increasing effective porosity, and restoring natural hydrophilicity, thereby improving adsorption and minimizing pore blockage. These findings highlight washed quartz as a structurally robust, scalable, and environmentally sustainable medium that can serve as a first-line barrier in multi-stage oily wastewater treatment systems. The slight yet meaningful efficiency gain with washed quartz demonstrates its industrial relevance, as even marginal improvements translate into significant operational benefits at scale. Overall, quartz offers a practical, low-cost alternative to conventional filtration materials, reducing the treatment burden on downstream polishing units and supporting water reuse in oil-intensive industries.

Keywords: Quartz particles, Pre-filtration media, Quartz pre-filtration, Oil/water separation, Surface cleaning, Industrial wastewater treatment.

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1. Introduction

Oil contamination in water poses a serious environmental threat. Each year, an estimated 6 million tons of oil enter the oceans from leaks and spills, devastating marine ecosystems. Beyond catastrophic spills, everyday industrial activities generate vast quantities of oily wastewater [1-3]. These effluents often form stable oil-in-water emulsions that are difficult to separate and can pollute water sources, harming aquatic life and human health. If discharged untreated, oily wastewater forms surface films that dissolved oxygen and raise the chemical oxygen demand in water bodies, causing severe damage to aquatic ecosystems. Unfortunately, over 80% of industrial wastewater worldwide is still released without adequate treatment, underscoring the urgent need for effective oil-removal solutions [3-5].

Developing efficient oil/water separation methods is critical for environmental protection and water reuse in arid regions, and such methods are also driven by regulations and sustainable water management [6, 7]. Conventional treatment techniques – physical, chemical, or biological – often struggle with stable emulsified oils and can be slow, energy-intensive, or costly [8, 9]. Membrane filtration can achieve high oil-removal efficiency, but oil fouling is a major challenge: oily droplets quickly clog membrane pores and coat surfaces, reducing permeability; even aggressive cleaning only partially restores performance and also shortens membrane lifespan while generating secondary waste [10-12]. Polymeric membranes are affordable but foul easily, whereas ceramic membranes are more fouling-resistant yet prohibitively costly and brittle for large-scale use [13-15].

Non-membrane approaches likewise demand high chemical and energy inputs and produce sludge waste. Consequently, it remains difficult to achieve a separation process that combines high efficiency, fouling resistance, and low operating cost [16, 17]. Membrane filtration is widely used and can produce high-quality effluent, but conventional membranes face serious operational challenges [18-20]. This challenge has prompted exploration of alternative low-cost media. Natural minerals have drawn attention to oil/water separation as low-cost filtration media. Quartz (crystalline SiO_2) has emerged as a promising candidate due to its abundance, low cost, and chemical stability [21-23].

Quartz sand has a long history in water purification – for example, 19th-century slow sand filters used quartz sand to purify drinking water – demonstrating its effectiveness and widespread availability. However, plain sand filtration is often insufficient for oily wastewater, as it requires large bed volumes and long residence times to achieve appreciable oil removal and still struggles with concentrated emulsions [24-26]. To improve quartz-based filtration, researchers have developed engineered quartz filters. For instance, sintered porous quartz membranes combine quartz's low cost and durability with greater mechanical strength and controlled pore size [27, 28]. Even with cleaning, heavily oil-fouled polymer membranes often suffer irreversible permeability loss [29, 30]. Quartz is naturally hydrophilic due to surface silanol (Si–OH) groups, giving it an inherent underwater oleophobic character (a water-wetted quartz surface resists oil adhesion). As a result, a quartz filter medium tends to stay water-wet during operation, which prevents oil from coating the grains and allows oil droplets to coalesce rather than foul the bed [30, 31]. This anti-fouling property helps maintain permeability and makes quartz filters easier to clean. Quartz is also low-cost: it is significantly cheaper than advanced ceramic membrane materials, and any required thermal processing can be done at relatively low temperatures, reducing fabrication energy costs. Using quartz can greatly reduce the material and production costs of filtration media without sacrificing performance [31, 32]. However, a quartz filter's performance depends strongly on its microstructural design. Key parameters include the grain size, packing arrangement (pore structure), and surface condition of the quartz media. Grain size determines pore size distribution and permeability: finer grains create smaller pores that trap smaller oil droplets but also increase flow resistance and risk rapid clogging. Conversely, coarser grains allow higher throughput but may let small, emulsified droplets escape unless droplet coalescence occurs. Optimizing the particle size distribution and bed depth greatly improves oil removal efficiency [33, 34]. For instance, using ~0.5 mm quartz sand in a 12.6 cm deep column achieved 98% oil removal, and oil droplets in the effluent were 2–3 times larger than those at the inlet – evidence of significant coalescence within the filter bed [35-37]. Despite these advantages, few studies have specifically examined quartz pre-filtration for oily wastewater, comparing untreated (raw) vs. acid-washed quartz media. This study evaluates quartz particles as a low-cost pre-filter, comparing raw versus acid-washed quartz and examining how surface cleanliness and microstructural characteristics affect oil removal efficiency. The aim is to demonstrate that a simple washing pretreatment can significantly boost quartz's filtration performance, highlighting quartz as an effective pre-filtration material in multi-stage oil/water separation systems.

2. Materials and Methods

2.1. Materials

Quartz particles were sourced from a local supplier and divided into two categories: raw quartz (as received) and washed quartz (acid-cleaned). The particles were dry-sieved to obtain a uniform size range of 0.8–1.8 mm, selected to balance permeability with adequate interfacial surface area for oil droplet capture. Washed quartz was prepared by rinsing with distilled water, followed by immersion in dilute hydrochloric acid to remove surface impurities, fines, and adhered residues. The material was then rinsed until neutral pH was achieved and oven-dried at 105 °C for 12 hours.

The oily wastewater emulsion used in this study was prepared by mixing industrial-grade lubricant oil with distilled water to achieve an initial oil and grease (O&G) concentration of 4393.80 mg/L, as determined using Standard Methods (APHA 5520B).

2.2. Experimental Setup

Filtration tests were conducted in a vertical glass column (20 cm packed-bed height) filled with quartz particles (0.8–1.8 mm). Influent oily wastewater was introduced at the top under gravity flow, and effluent samples were collected at the outlet. Separate runs were performed for raw and washed quartz under identical hydraulic conditions. Between runs, the system was flushed with distilled water to avoid cross-contamination.

Figure 1 illustrates the experimental setup, showing the influent oil/water mixture entering the quartz-packed column, percolating through the bed, and exiting as treated water at the bottom.

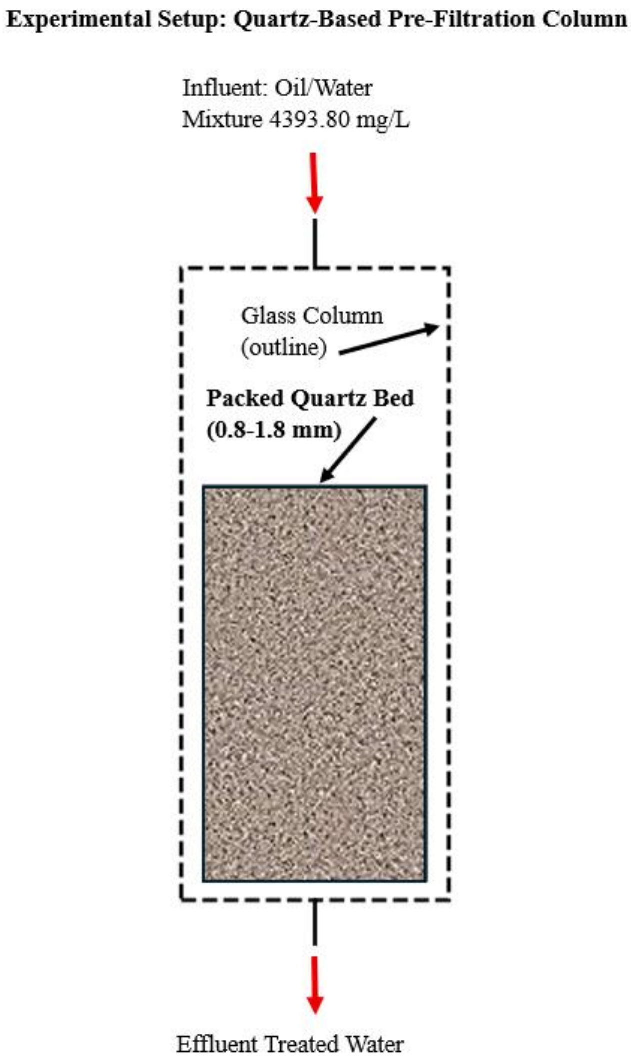

Figure 1.
Schematic representation of the quartz-based pre-filtration column used in this study, showing influent oil/water mixture, quartz bed (0.8–1.8 mm), and effluent outlet.

3. Analytical Methods

Oil and grease (O&G) concentrations for influent and effluent were quantified following *Standard Methods* APHA 5520 B (solvent extraction–gravimetric). Briefly, samples were acidified to pH < 2, extracted with n-hexane, the organic phase was evaporated to constant mass, and the residue was weighed. Concentrations are reported as $mg \cdot L^{-1}$. All measurements were performed in triplicate, with blanks included to confirm no carry-over.

3.1. Performance Metrics

Filtration performance was evaluated using conventional and derived metrics.

Let C_{in} $(mg \cdot L^{-1})$ denote the influent O&G concentration and $C_{\text{out},j}$ the effluent O&G concentration for condition j (raw or washed quartz). Bed depth is L (m).

(1) Percentage oil removal (baseline, reported for completeness)

$$\eta_j(\%) = 100\left(1 - \frac{C_{\text{out},j}}{C_{\text{in}}}\right) \quad (1)$$

(2) Pre-Filtration Improvement Factor (PIF) a simple amplification ratio preferred for pre-filters:

$$\mathrm{PIF}_j = \frac{C_{\mathrm{in}}}{C_{\mathrm{out},j}} \qquad (2)$$

(A higher PIF indicates greater improvement in effluent quality.)

(3) Depth-Normalized Removal (DNR) removal intensity per unit bed height (intensive, scale-independent):

$$\mathrm{DNR}_j = \frac{C_{\mathrm{in}} - C_{\mathrm{out},j}}{C_{\mathrm{in}}\, L} \quad [\mathrm{m}^{-1}] \qquad (3)$$

where L is the packed-bed depth (m). This index allows scale-independent comparison of removal performance (Useful for comparing columns of different heights or for scale-up).

4. Results

The performance of quartz particles as a low-cost pre-filtration medium for oil/water separation was systematically evaluated by comparing raw and washed quartz within the particle size range of 0.8–1.8 mm. The influent oily wastewater exhibited a very high initial oil concentration of 4393.80 mg/L, representing a severe pollution load typical of industrial effluents. Following filtration through raw quartz, the oil concentration in the effluent decreased substantially to 85.00 mg/L, corresponding to a removal efficiency of 98.07%. A further improvement was observed with washed quartz, where the effluent concentration was reduced to 66.60 mg/L, achieving a removal efficiency of 98.48%. These results demonstrate that quartz, particularly after surface cleaning, can significantly reduce oil concentrations to levels more manageable for downstream polishing treatments. The following subsections present detailed comparisons of influent and effluent characteristics, supported by visual and tabular data (Figures 2–6, Table 1), to highlight the influence of surface cleanliness and microstructural properties on separation efficiency.

SEM-EDS analysis of raw quartz (Figure 2) revealed an irregular, rough surface morphology with localized impurities. The elemental maps confirmed Si and O as the dominant elements, consistent with the quartz (SiO_2) structure, while trace Al and P were also detected in small regions. These impurities are likely present as aluminosilicate inclusions or surface contaminants, which may affect surface wettability and partially obstruct pore spaces. The corresponding EDS spectrum (Figure 3) supported these findings, showing strong Si-K and O-K peaks alongside minor Al-K and P-K signals. A small C-K peak was also observed, attributed to sample preparation rather than intrinsic composition.

Overall, the combined results confirm that raw quartz is predominantly silica-rich but contains trace impurities that could limit adsorption efficiency, helping to explain its slightly lower oil removal performance compared to washed quartz.

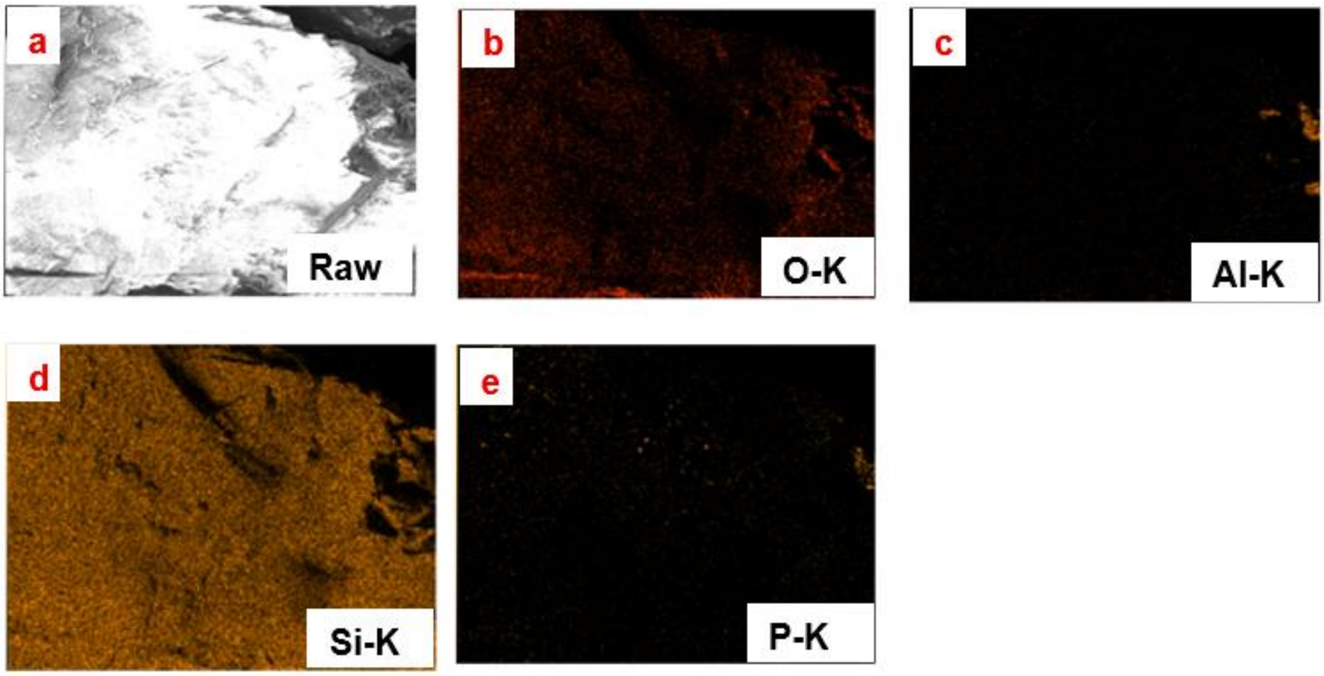

Figure 2.
SEM-EDS elemental mapping of raw quartz particles: (a) backscattered electron image, (b) O-K map, (c) Al-K map, (d) Si-K map, and (e) P-K map. The distribution confirms Si and O as the major constituents of quartz, with minor traces of Al and P indicating impurities.

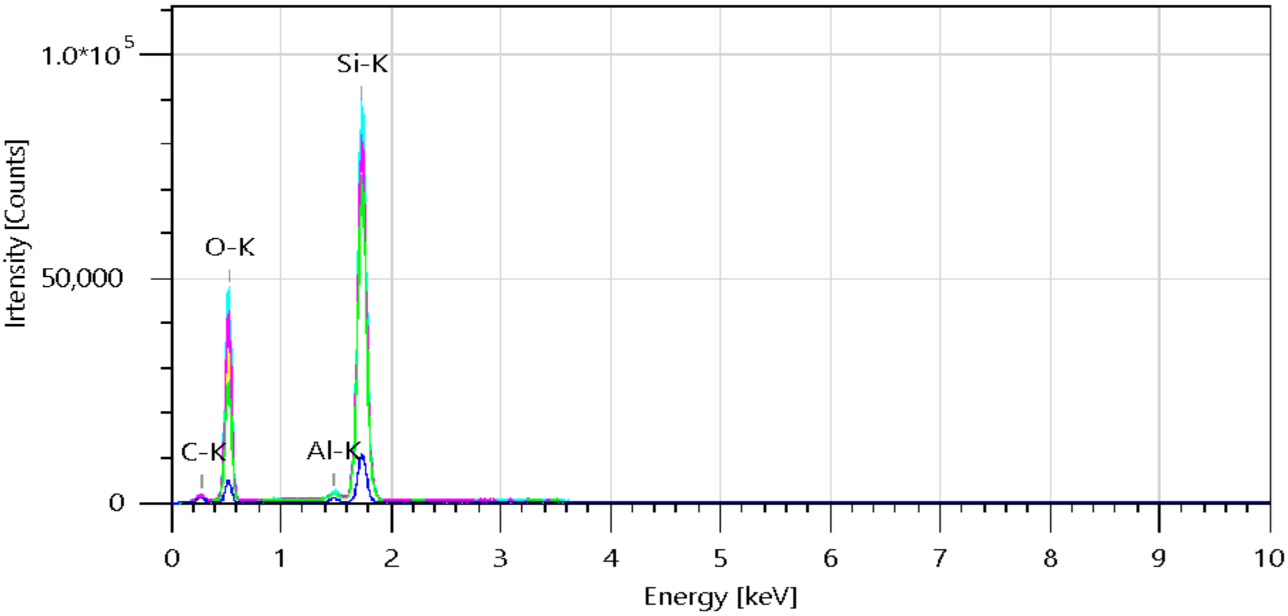

Figure 3.
Energy-dispersive X-ray (EDS) spectrum of raw quartz. Dominant peaks at Si-K (~1.74 keV) and O-K (~0.52 keV) confirm SiO_2 as the principal phase; a minor Al-K (~1.49 keV) peak indicates aluminosilicate impurities. A small C-K (~0.28 keV) signal is attributed to the carbon tape/organic residues used during mounting rather than to the mineral itself.

SEM-EDS analysis of washed quartz (Figure 4) revealed a smoother, cleaner surface compared to raw quartz, indicating that the acid washing process effectively removed loosely bound impurities. The elemental maps showed Si and O as the dominant constituents, with stronger and more homogeneous distributions than in the raw sample. In contrast, the Al signal, clearly visible in raw quartz, was greatly diminished after washing, confirming the removal of aluminosilicate impurities. The phosphorus signal remained detectable but at low intensity, suggesting only trace residuals. A minor C signal was also observed, which is likely due to sample preparation rather than intrinsic composition.

The corresponding EDS spectrum (Figure 5) supported these observations, showing prominent Si-K and O-K peaks with significantly reduced Al-K intensity compared to the raw quartz spectrum. The P-K peak was still present but weak, while the C-K peak was again attributed to external residues. Together, these results confirm that washing enhances the purity of quartz by reducing surface impurities and exposing more active Si–O sites. This compositional refinement directly explains the superior oil removal efficiency of washed quartz, which achieved an effluent concentration of 66.60 mg/L compared to 85.00 mg/L for raw quartz.

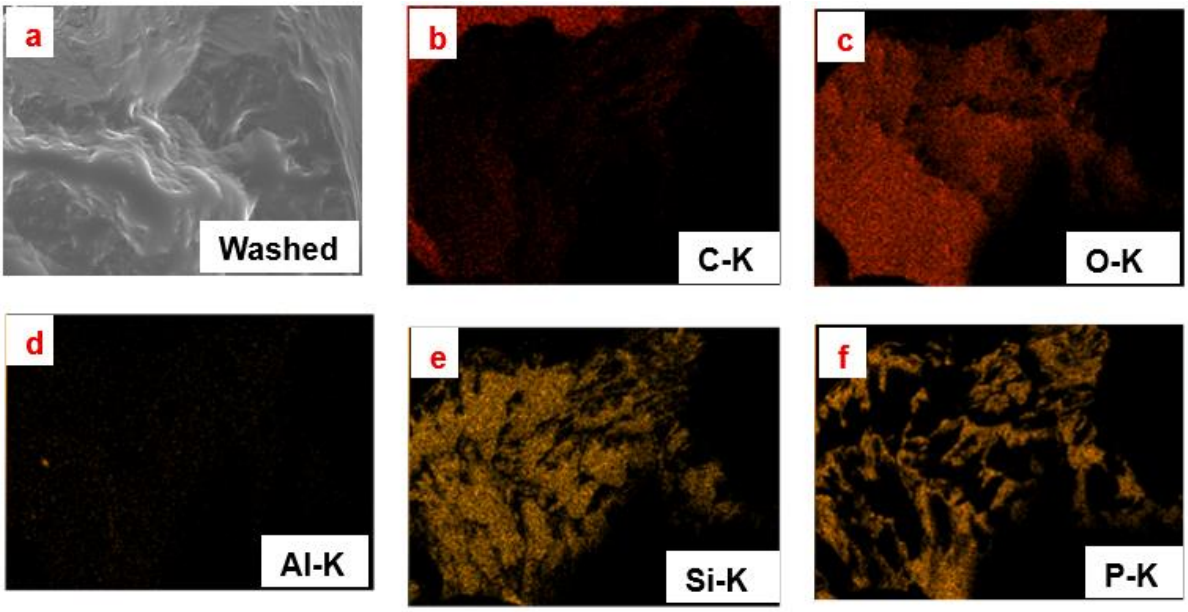

Figure 4.
SEM-EDS elemental mapping of washed quartz particles: (a) backscattered electron image, (b) C-K map, (c) O-K map, (d) Al-K map, (e) Si-K map, and (f) P-K map. The washed sample shows a clearer surface with enhanced Si and O distribution and diminished impurity signals compared to the raw quartz.

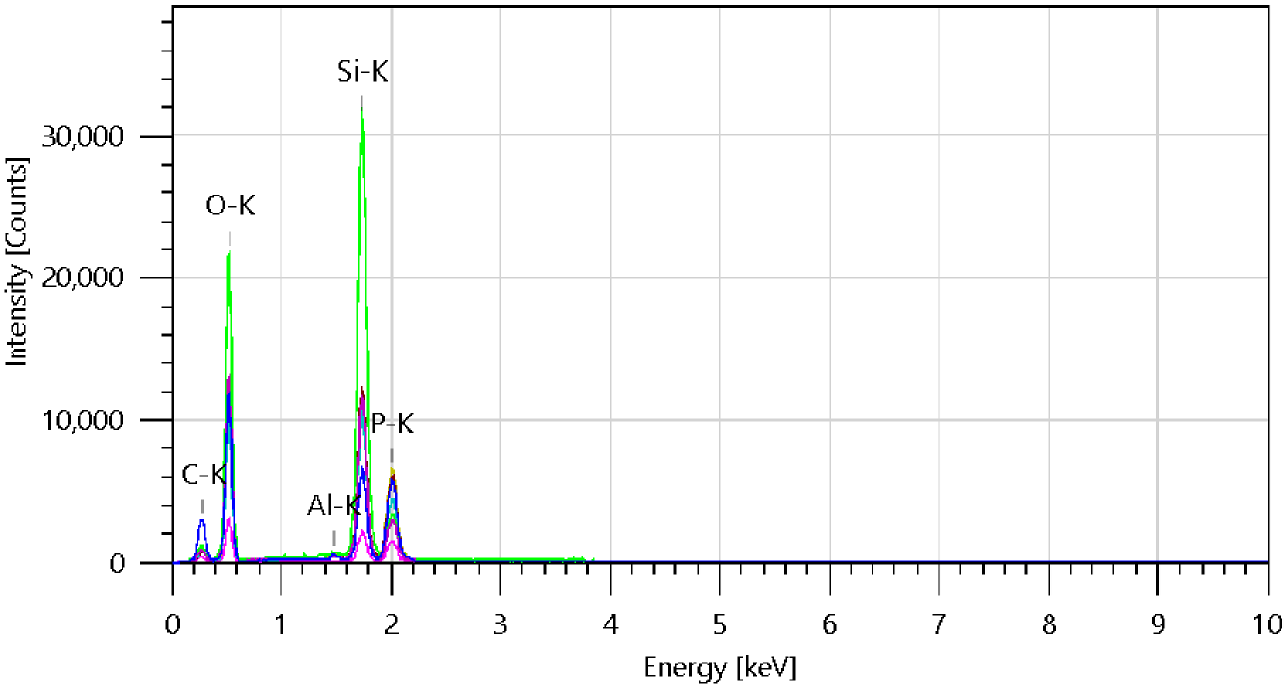

Figure 5.
EDS spectrum of washed quartz particles showing dominant peaks for Si and O, with minor signals for C, Al, and P. The spectrum confirms that Si and O are the principal constituents of the quartz framework, while the reduced intensity of Al compared to raw quartz indicates removal of aluminosilicate impurities after washing.

Table 1 shows a remarkable reduction in oil concentration from the influent (4393.80 mg/L) to the effluents treated with raw quartz (85.00 mg/L) and washed quartz (66.60 mg/L), corresponding to oil removal efficiencies of 98.06% and 98.48%, respectively. These results align closely with the SEM-EDS elemental mapping and EDS spectra in Figures 2–5. For raw quartz (Figures 2 and 3), Si and O were confirmed as the major elements, but the presence of Al and P impurities likely restricted surface activation and pore accessibility, resulting in slightly higher residual oil concentration. In contrast, washed quartz (Figures 4 and 5) exhibited cleaner surfaces with more prominent Si–O sites and reduced impurities, as shown by the improved elemental distribution and EDS spectra. This enhanced purity facilitated better interaction with oil droplets and improved trapping efficiency, leading to marginally higher oil removal.

Although both raw and washed quartz achieved outstanding efficiencies above 98%, the washed quartz demonstrated a slight but meaningful improvement, confirming that surface cleaning enhances quartz activity and adsorption performance. This advantage, though subtle, positions washed quartz as the more reliable medium for potential upscaling and industrial application, where even minor efficiency gains can translate into significant operational and environmental benefits.

Table 1.
Oil concentration in influent and effluent after treatment with raw and washed quartz media.

Samples	Oil concentration mg/L	Interpretation
Oil and water mixture	4393.80	Represents the initial influent before treatment, showing extremely high oil loading that requires separation.
Raw quartz	85.00	Raw quartz reduced oil concentration significantly, indicating its effectiveness as a filtration medium. However, residual impurities and limited surface activation restricted maximum oil removal efficiency.
Washed quartz	66.60	Washed quartz achieved lower effluent oil concentration compared to raw quartz, confirming that surface cleaning improved quartz activity and pore accessibility, leading to enhanced oil removal performance.

Figure 6 illustrates the oil concentration before and after treatment with raw and washed quartz media. The influent oil and water mixture initially contained a very high oil concentration of 4393.80 mg/L, indicating heavy pollution requiring treatment. After filtration, the effluent concentration was significantly reduced to 85.00 mg/L using raw quartz, corresponding to an oil removal efficiency of approximately 98.07%. Further improvement was observed with washed quartz, which lowered the oil concentration to 66.60 mg/L, achieving a slightly higher removal efficiency of 98.48%. These results demonstrate that quartz, particularly after washing, is an effective low-cost medium for oily wastewater treatment, as surface cleaning enhances pore accessibility and adsorption sites, thereby improving overall performance.

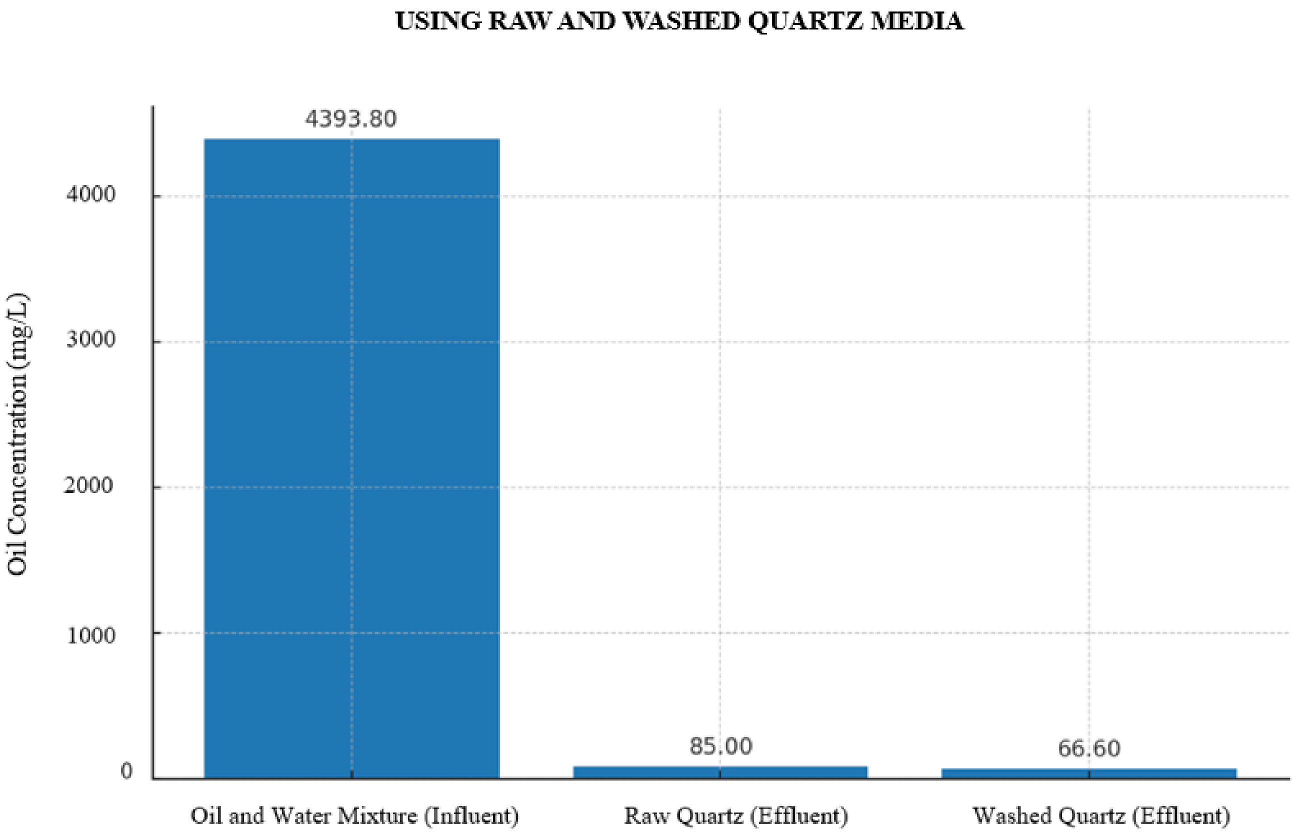

Figure 6.
Oil concentration in influent and effluent after treatment with raw and washed quartz media.

5. Discussion

5.1. Raw vs. Washed Quartz Comparison

Both raw and acid-washed quartz media demonstrated high oil removal efficiencies, lowering influent concentrations from ~4394 mg/L to below 100 mg/L. Raw quartz achieved 98.07% removal, while washed quartz slightly outperformed with 98.48%. Although the efficiency difference appears modest, it is significant for large-scale applications where even fractional improvements can reduce treatment costs and extend the lifespan of downstream processes.

SEM-EDS confirmed that raw quartz surfaces contained trace aluminum and phosphorus impurities, whereas washing produced cleaner, more uniform Si–O surfaces. This compositional refinement explains the marginally superior performance of washed quartz and highlights the importance of surface quality in filtration media [38, 39].

5.2. Mechanism of Improvement

The improved performance of washed quartz is attributed to microstructural and chemical changes induced by acid treatment. Removal of impurities enhances effective porosity and restores the natural hydrophilicity of quartz by exposing silanol (Si–OH) groups. This hydrophilic character prevents oil adhesion, reduces fouling, and facilitates droplet coalescence within the filter bed. Furthermore, the elimination of fines and loosely bound residues minimizes pore blockage, maintaining permeability and adsorption efficiency. These microstructural benefits align with broader findings that particle surface modifications improve wettability, reduce fouling, and strengthen long-term stability of filtration media. In essence, acid washing optimizes quartz's inherent surface properties, transforming an already effective material into a more reliable and robust pre-filtration medium [40, 41].

5.3. Scalability and Industrial Implications

Quartz's abundance, durability, and low preparation cost make it highly suitable for scale-up compared to polymeric and ceramic membranes. The scalability framework (Table 2) illustrates that quartz can sustain efficiencies above 90% across laboratory, pilot, and industrial systems, even under high influent oil loads. While ceramic and polymeric membranes remain valuable for final polishing, quartz pre-filtration offers a cost-effective barrier that reduces oil concentration by two orders of magnitude, alleviating the burden on advanced treatment units. The slight but consistent improvement observed with washed quartz confirms that surface preparation is critical to maximizing industrial performance. At scale, these enhancements translate into lower operational costs, reduced fouling frequency, and improved sustainability in oily wastewater management [42-44].

Table 2.
Conceptual up scalability framework of quartz-based pre-filtration systems for oily wastewater treatment.

Scale	Bed Volume (L)	Expected Flow Rate (L/h)	Oil Removal Efficiency (%)	Application Context	Remarks
Laboratory	1–5	1–5	98.0–98.5	Bench-scale trials	Demonstrates proof-of-concept and performance testing
Pilot	50–500	20–200	95–98	Small industries (e.g., workshops, garages)	Allows optimization of flow distribution and pressure drop
Industrial	1000–10,000	500–5000	90–95	Large-scale industries (e.g., petrochemical, mining)	Cost-effective bulk oil removal before advanced polishing
Municipal	>50,000	>10,000	85–90	City-level wastewater treatment	Integrates as pretreatment to reduce oil loading in centralized plants

6. Conclusion

This study demonstrated the effectiveness of quartz particles (0.8–1.8 mm) as a low-cost, robust pre-filtration medium for oily wastewater treatment. Both raw and acid-washed quartz achieved excellent oil removal efficiencies (>98%), reducing influent concentrations from ~4394 mg/L to below 100 mg/L. Acid washing provided a slight but consistent improvement (98.07% to 98.48%), attributed to removal of surface impurities, enhanced porosity, and restored hydrophilicity. These findings validate quartz as a scalable, sustainable alternative to conventional polymeric and ceramic membranes, offering a practical first-line barrier that alleviates the burden on downstream polishing units.

Looking ahead, future work should explore optimizing quartz particle size distribution to balance permeability and adsorption capacity, as well as surface functionalization strategies to tailor wettability for diverse industrial effluents. Long-term durability studies under cyclic loading and variable operating conditions will also be essential to confirm stability and regeneration potential. Together, these directions will advance the development of quartz-based pre-filtration systems toward industrial deployment and broader water reuse applications.

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