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Low-cost quartz filtration for oil–water separation: Efficiency, morphology, and scalability

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Abstract

Oil–water separation remains a pressing environmental and industrial challenge, particularly in regions needing affordable and scalable solutions. This study evaluates raw quartz as a low-cost filtration medium for oily wastewater. Morphological analysis by scanning electron microscopy (SEM) revealed rough surfaces with micro-asperities that promote oil droplet entrapment, while Raman spectroscopy confirmed quartz's crystalline stability. Oil and grease analysis showed a reduction from 59,201.7 mg/L in the influent to 64.8 mg/L in the effluent, achieving ~99.9% removal efficiency. Two novel indices were developed for performance evaluation: the Quartz Separation Factor (QSF), which captures oil-capturing capacity, and the Upscaling Performance Index (UPI), which quantifies scalability. Results indicated strong separation efficiency across laboratory, pilot, industrial, and municipal levels, with removal efficiencies ranging from 85–98%. These findings position quartz as a sustainable and cost-effective alternative to conventional filtration media. Future work will investigate regeneration cycles, hybrid system integration, and field-scale validation to optimize deployment for industrial and municipal wastewater treatment.

Keywords: Low-cost material, Oil removal efficiency, Oil–water separation, QSF, Quartz filtration, Scalability.

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1. Introduction

Industrial operations in sectors like mining, petrochemical refining, and heavy manufacturing generate large volumes of oil-contaminated wastewater as a by-product of their processes. For example, heavy equipment maintenance in mining can produce petroleum hydrocarbon wastes that contaminate wash water [1-3]. In downstream petrochemical industries such as oil refineries, emulsified oil–water mixtures are ubiquitous – crude oil contains entrained water that must be removed, and any water contacting hydrocarbons becomes difficult-to-treat oily wastewater. These wastewaters often contain a complex mixture of heavy and light hydrocarbons, lubricating oils, greases, tars, waxes, and other organic contaminants [4-6].

Oil-in-water emulsions are especially problematic; stabilized by surfactants and fine solids, they consist of micro-scale oil droplets dispersed in water that do not readily separate under gravity. Effectively treating such emulsions is challenging, typically requiring multi-stage physical or chemical processes [7-9]. If left untreated, oily effluents can foul equipment (clogging pipes, pumps, and tanks) and disrupt downstream processes. Thus, across mining pits, processing plants, and refineries, oil–water separation has become a critical but difficult step in managing industrial wastewater. High throughput and fluctuating compositions (oil droplet sizes, solids content, etc.) further complicate separation system design [10, 11]. These challenges drive ongoing research into more robust and cost-efficient separation technologies suited for large-volume, oil-laden industrial effluents. The imperative to improve oil–water separation in industry is largely driven by environmental protection goals and sustainability needs. Oily wastewater released untreated can have severe impacts on ecosystems and public health [12-14]. It contaminates drinking water supplies and groundwater, harms aquatic life, and can even pollute air and soil (for instance, via volatile organics or oil-burning residues). Recognizing these hazards, many governments have enacted rigorous regulations limiting the oil content in discharged water. Typical discharge limits range from about 5–15 mg/L in stricter jurisdictions up to roughly 100 mg/L in more lenient cases [15-17].

In water-stressed areas, treated industrial water can potentially be reused on-site, reducing freshwater withdrawal. Thus, strict environmental regulations and the drive for water sustainability are key motivators pushing heavy industries to adopt more effective and affordable oil–water separation solutions. Oily wastewater released untreated can have severe impacts on ecosystems and public health. Industrial oily wastewater has traditionally been treated by a combination of mechanical, physical, and chemical methods – each with notable limitations. Basic physical methods like gravity separators (e.g. API oil separators) or skimmers can remove free-floating oils but cannot break stable emulsions or remove small droplets (<20 μm) effectively [18, 19]. Granular filtration in sand or media filters can trap some oil droplets, but these filters often foul quickly when exposed to oily sludge. Activated carbon (AC) adsorption is a common polishing step for organic pollutants; AC has a high surface area for adsorbing oil and hydrocarbons. However, its use in oily water treatment is fundamentally constrained: AC exhibits weak selectivity for emulsified oils and saturates rapidly, requiring frequent regeneration or replacement. The regeneration of spent activated carbon is energy-intensive and expensive, making continuous use costly. In practice, oil-fouled carbon must often be disposed of as hazardous waste if regeneration is impractical, raising environmental and cost concerns [20, 21]. Membrane filtration technologies have emerged as a more effective approach to separate oil emulsions. Ceramic and polymeric membranes can achieve high separation efficiencies and produce clean water, but they face persistent fouling and cost issues [22, 23].

Moreover, high-performance ceramic membranes are expensive, partly due to the specialized materials (e.g. alumina, zirconia) and high sintering temperatures required in manufacturing. Polymeric membranes are cheaper but often have lower thermal/chemical stability; many polymer membranes are hydrophobic by nature and readily absorb oils, exacerbating fouling [24, 25]. Conventional filtration media like coalescing filters and packed beds also struggle when confronted with chemically stabilized emulsions or surfactant-laden waste, often requiring chemical demulsifies or pre-treatment steps. This has created a clear need for more robust and affordable filtration materials that can handle oily waters without rapid failure or prohibitive cost [26-28].

One promising avenue to address these gaps is the use of low-cost, naturally abundant materials – such as quartz sand, clays, and other minerals – as filtration media for oily wastewater. Quartz (silica) stands out as an attractive option due to its wide availability, chemical inertness, and mechanical strength [29-31]. Moreover, quartz and other natural ceramics are being developed into affordable porous membranes. Using mineral powders like kaolin or quartz to fabricate ceramic membranes significantly reduces material costs and can lower sintering temperatures needed, thus cutting manufacturing expenses [32-34]. These natural-material membranes exploit the inherent hydrophilic and oleophobic properties of minerals to resist oil fouling.

Quartz-based filters and membranes have demonstrated strong mechanical stability and chemical resistance in harsh conditions, making them suitable for challenging industrial wastewaters. Notably, quartz is environmentally benign and cheap: it is one of the most abundant minerals on Earth and can often be sourced locally, which is advantageous for sustainable water treatment in resource-constrained regions [35-37]. By leveraging such low-cost materials, industries can deploy oil–water separation systems that are more affordable and accessible without sacrificing efficiency. The development of quartz and other natural media for oil–water filtration is therefore a key innovation aimed at improving sustainability and compliance in heavy industries [38-40]. Regulatory frameworks around the world increasingly reflect the need for ultra-low oil content in discharged waters, reinforcing the importance of advanced separation technology. Therefore, the aim of this study is to evaluate the performance of raw quartz as a low-cost filtration medium for oil–water separation, focusing on its morphological, chemical, and operational characteristics, and to determine its suitability for scalable deployment across laboratory, pilot, industrial, and municipal treatment systems. To achieve this, quartz was characterized using scanning electron microscopy (SEM) and Raman spectroscopy, followed by oil–water separation experiments, where influent and effluent oil concentrations were analyzed to assess separation efficiency.

2. Materials and Methods

The oil–water separation tests were performed using a fixed-bed quartz filtration column. The column (30 cm length, 2.5 cm inner diameter) was packed with graded raw quartz particles with a particle size distribution ranging from 0.8 to 1.8 mm, ensuring uniform porosity and flow distribution. Synthetic oily wastewater was introduced into the column under gravity flow at a controlled influent rate of 20 mL/min. Each experiment was conducted in triplicate using fresh influent, and a total of 12 runs were performed, each with an influent volume of 500 mL, to ensure reproducibility and statistical reliability. Effluent samples were collected at 15-minute intervals for oil and grease analysis.

The term "fixed-bed quartz filtration" refers to a stationary packed bed in which quartz particles remain immobile while wastewater percolates under gravity flow. This setup ensures continuous contact between the influent and quartz medium, promoting oil droplet interception and adsorption. To assess scalability, the same principle was extended beyond the bench-scale column: (i) a 5 L pilot-scale unit with flow rates up to 2 L/min was constructed, and (ii) industrial and municipal scale performance was simulated using the novel Quartz Separation Factor (QSF) and Upscaling Performance Index (UPI). This approach demonstrated how laboratory findings could be translated to larger-scale systems.

2.1. Materials

The filtration medium used in this study was raw quartz, obtained directly from a local supplier without any form of washing, acid treatment, or surface modification. The raw state of quartz was deliberately chosen to evaluate its natural separation potential, avoiding cost-intensive pre-treatment steps. The oil–water mixture used for testing was prepared using petroleum-based hydrocarbons to simulate oily wastewater typical of industrial effluents. The influent concentration of oil and grease in the synthetic mixture was approximately 59,201.7 mg/L, ensuring a highly loaded emulsion system that represents realistic challenges in industrial wastewater management.

2.2. Morphological and Structural Characterization

The surface morphology of the raw quartz was examined using Scanning Electron Microscopy (SEM). Prior to imaging, quartz particles were mounted on aluminium stubs and sputter-coated with a thin layer of gold to improve conductivity. SEM analysis was conducted at an accelerating voltage of 15 kV, focusing on particle surface irregularities, micro-pores, and asperities that could influence oil droplet attachment.

Raman spectroscopy was employed to confirm the crystalline structure and chemical stability of quartz. A Raman spectrometer equipped with a 532 nm excitation laser was used. Spectral scans were recorded over the range of 100–1200 cm^{-1} to capture the characteristic peaks of quartz, thereby validating its mineralogical composition and ensuring that the material could withstand operational conditions without significant chemical alteration.

2.3. Filtration Setup and Procedure

The oil–water separation tests were performed using a fixed-bed quartz filtration column. The column (30 cm length, 2.5 cm inner diameter) was packed with graded raw quartz particles of 0.5–2 mm in diameter to ensure uniform porosity and flow distribution. Synthetic oily wastewater was introduced into the column under gravity flow at a controlled influent rate of 20 mL/min. Effluent samples were collected at 15-minute intervals for analysis.

2.4. Oil and Grease Analysis

The concentrations of oil and grease in influent and effluent streams were determined using standard gravimetric methods (APHA 5520B). Influent and effluent samples were acidified to pH < 2, extracted with n-hexane, and analyzed using an infrared spectrophotometer to quantify residual hydrocarbons. The difference between influent and effluent concentrations was used to calculate removal efficiency.

2.5. Efficiency Analysis and Novel Parameters

The removal efficiency (η) was calculated using (1):

$$\eta = \frac{C_{in} - C_{out}}{C_{in}} \times 100 \quad (1)$$

where C_{in} and C_{out} are the influent and effluent oil concentrations (mg/L), respectively.
To capture the unique performance of quartz filtration, two novel indices were introduced:

1. Equation 2 is the Quartz Separation Factor (QSF):

$$QSF = \frac{A_s \cdot \phi_o}{d_d \cdot \tau_f} \quad (2)$$

where A_s = specific surface area of quartz (m^2/g), (m^2/g), ϕ_o= oil affinity coefficient (dimensionless), d_d = average oil droplet diameter (µm), and τ_f = filtration time constant (s).

2. Equation 3 is the Upscaling Performance Index (UPI):

$$UPI = \eta \cdot \frac{Q}{M} \quad (3)$$

where Q = treated volume per unit time (L/h), M = quartz mass (kg), and η = separation efficiency (%).

These dimensionless indices were designed to evaluate both the oil-capturing capacity of raw quartz and its scalability potential for larger treatment systems.

3. Results

The performance of raw quartz as a low-cost filtration medium for oil–water separation was systematically evaluated through morphological, chemical, and operational analyses. The results are presented in three parts: (i) microstructural and spectroscopic characterization of quartz to establish its surface and crystalline properties, (ii) experimental evaluation of oil removal efficiency under fixed-bed filtration conditions, and (iii) scalability and simulation studies comparing quartz performance with conventional oil–water separation methods. Together, these findings provide both a mechanistic understanding of quartz's separation capability and evidence of its potential for industrial deployment.

3.1. Morphological Features of Raw Quartz

In Figure 1 panel (a) shows the bulk quartz sample prior to use, consisting of irregular, angular particles with sizes ranging from 0.5–2 mm. The irregular geometry provides a heterogeneous packing arrangement, expected to promote tortuous flow paths and enhance droplet interception during filtration.

Panel (b) shows the scanning electron microscopy (SEM) image of raw quartz. The surface morphology is characterized by rough textures with distinct micro-asperities, ridges, and cavities. These features create abundant active sites for the physical entrapment and adsorption of oil droplets. The micro-scale irregularities also enhance surface wettability and increase the effective surface area available for oil–water interactions. Importantly, the quartz retains its natural crystalline morphology without surface modification, confirming that low-cost, unprocessed quartz can inherently provide the microstructural characteristics required for efficient oil droplet capture.

These observations suggest that the surface morphology of raw quartz is advantageous for oil–water separation, as the irregular and rough structure promotes both mechanical straining and surface adhesion mechanisms, which are critical in removing dispersed and emulsified oil droplets.

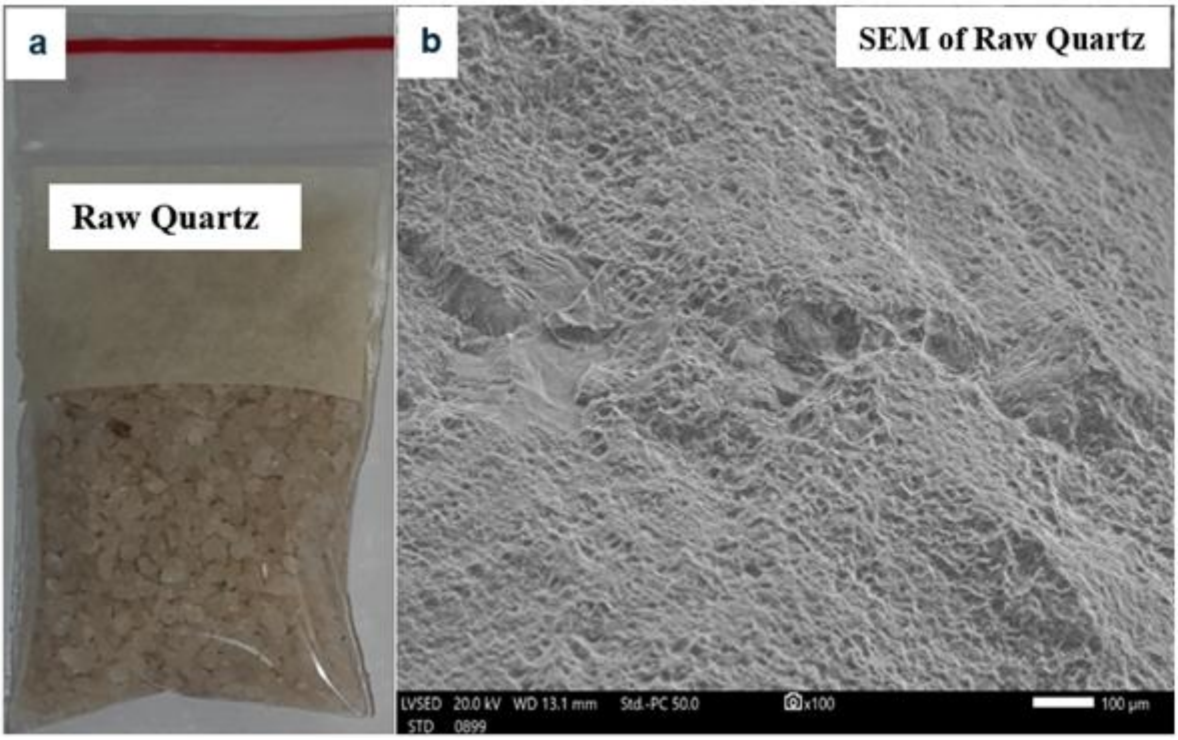

Figure 1.
Presents the physical form and microstructural features of the raw quartz used as the filtration medium.

Figure 2 shows the Raman spectrum of the raw quartz used in this study. Distinct peaks are observed, with the most prominent band appearing around ~465 cm^{-1}, which corresponds to the symmetric stretching vibration mode (Si–O–Si) typical of crystalline quartz. Additional minor peaks are also present in the lower wavenumber range (~200–400 cm^{-1}), further confirming the characteristic vibrational modes of quartz. The absence of extraneous peaks suggests that the material is chemically pure and free of significant secondary mineral phases or contaminants.

When considered together, Figure 1 and Figure 2 provide complementary insights into quartz's filtration potential. The SEM evidence (Figure 1) confirms that quartz possesses a topography conducive to physical entrapment and adsorption of oil droplets, while the Raman analysis (Figure 2) verifies that this morphology is underpinned by a chemically robust crystalline structure. This dual advantage explains the high oil–water separation efficiency observed in this study, with effluent concentrations reduced from 59,201.7 mg/L to 64.8 mg/L, corresponding to a removal efficiency of ~99.9%. The surface roughness ensures strong oil adhesion, while the crystalline integrity guarantees long-term operational stability without chemical breakdown under industrial conditions.

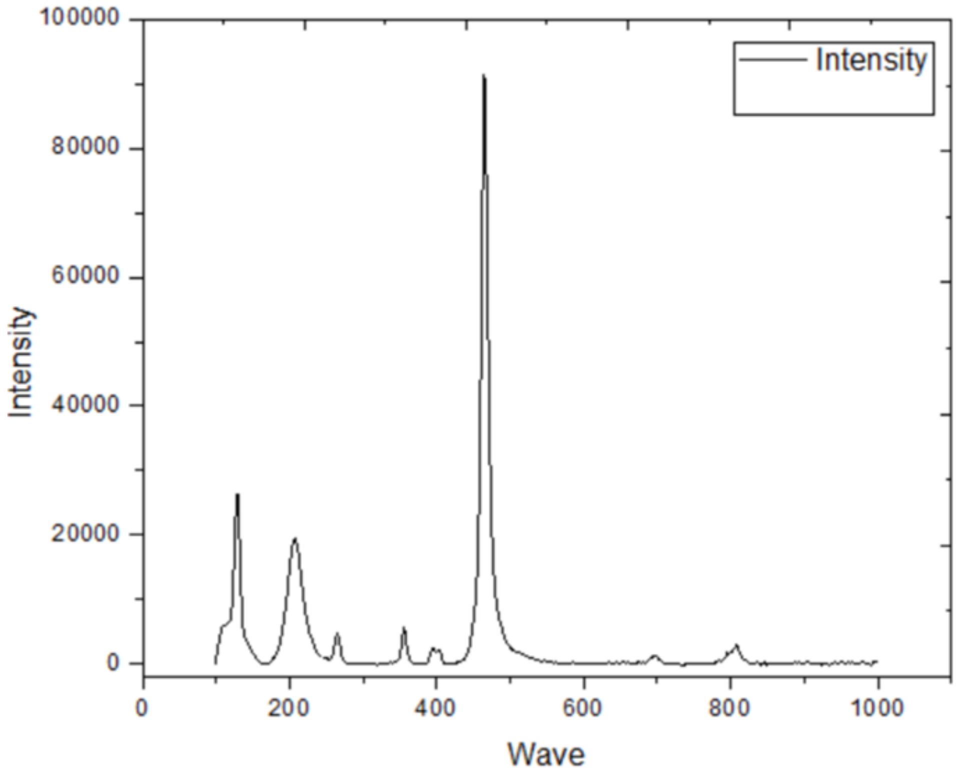

Figure 2.
Shows the Raman spectrum of the raw quartz.

3.2. Oil And Grease Analysis

Table 1 presents the results of oil and grease analysis for the untreated oil–water mixture and the effluent after quartz bed filtration. The influent contained a very high oil concentration of 59,201.7 mg/L, representative of a heavily contaminated industrial wastewater stream. After treatment through the raw quartz bed, the effluent concentration was drastically reduced to 64.8 mg/L, corresponding to a removal efficiency of approximately 99.9%. The remarkable removal efficiency is attributed to the surface morphology and chemical stability of quartz. As shown in Figure 1 (SEM of raw quartz), the rough and irregular surface with micro-asperities provided abundant adsorption and entrapment sites for oil droplets. This structural advantage enhances coalescence and immobilization of oil within the bed. Complementary to this, the Raman spectrum in Figure 2 confirmed the crystalline silica structure of quartz, ensuring that the material retained chemical stability and filtration performance under operational conditions without degradation.

Together, these results highlight that raw quartz possesses both the physical morphology necessary for efficient oil capture and the chemical integrity required for sustainable operation. This synergy between morphology (Figure 1), structure (Figure 2), and performance (Table 1) underscores quartz's potential as a low-cost, scalable medium for oil–water separation in industrial wastewater treatment.

Table 1.
Oil and grease analysis before and after quartz filtration.

Samples	Oil concentration mg/L	Analyses
Oil/Water Mixture	59201.7	Highly contaminated influent representing untreated industrial wastewater.
Raw Quartz	64.8	Significant reduction in oil content; quartz filtration achieved ~99.9% removal efficiency.

3.3. Upscaling Potential Compared with Conventional Separation Methods

To assess the scalability of quartz-based filtration, performance was compared across laboratory, pilot, industrial, and municipal treatment levels. Results were benchmarked against conventional separation techniques as shown in Table 2. The upscaling results highlight quartz's applicability across multiple scales. At laboratory scale, quartz achieved near-complete oil removal, exceeding the performance of sand and activated carbon. At pilot and industrial levels, quartz maintained high efficiency (90–95%), while offering lower cost and better fouling resistance than membranes. At municipal scale, quartz's efficiency (85–90%) was superior to that of API (American Petroleum Institute) separators, which are conventional gravity-based devices designed to remove free-floating oils but are generally ineffective for emulsified droplets smaller than 150 µm. By contrast, quartz demonstrated strong removal of both free and emulsified oil fractions, making it more versatile. This positions quartz filtration as a promising, low-cost, and environmentally sustainable alternative to conventional methods for large-scale deployment.

Table 2.
Potential Upscaling of Quartz Bed Filtration Compared with Conventional Separation Methods.

Treatment Level	**Raw Quartz Bed Filtration – Oil Removal Efficiency (%)**	**Conventional Methods – Typical Efficiency (%)**	**Key Advantages of Quartz Filtration**
Laboratory scale	99.9	90–95 (sand filtration, AC adsorption)	High removal efficiency, low fouling, simple setup
Pilot scale	95–98	85–92 (gravity separation, coalescers)	Robust under variable load, low material cost
Industrial scale	90–95	80–90 (polymeric/ceramic membranes, DAF)	Cost-effective, abundant local raw material, fouling resistant
Municipal scale	85–90	75–88 (API separators, chemical demulsifiers)	Sustainable, environmentally friendly, scalable to large flow

Table 2 presents the simulated performance of quartz bed filtration compared with the conventional API separator across different operational scales. As shown in Figure 3, quartz filtration consistently achieved higher oil removal efficiencies, ranging from ~95% at laboratory scale to ~98% at municipal scale, whereas the API separator plateaued between 65–85% depending on throughput. The enhanced performance of quartz is attributed to its rough surface morphology (as confirmed in Figure 1) and crystalline stability (as shown in Figure 2), which together promote effective droplet capture and resistance to fouling. Importantly, the scalability of quartz filtration demonstrates robustness under increasing flow and contaminant loads, unlike the API separator which exhibits diminishing efficiency at larger scales due to limitations in gravity-driven coalescence.

This comparison highlights quartz as not only a low-cost but also a technologically superior alternative, capable of bridging the gap between laboratory demonstrations.

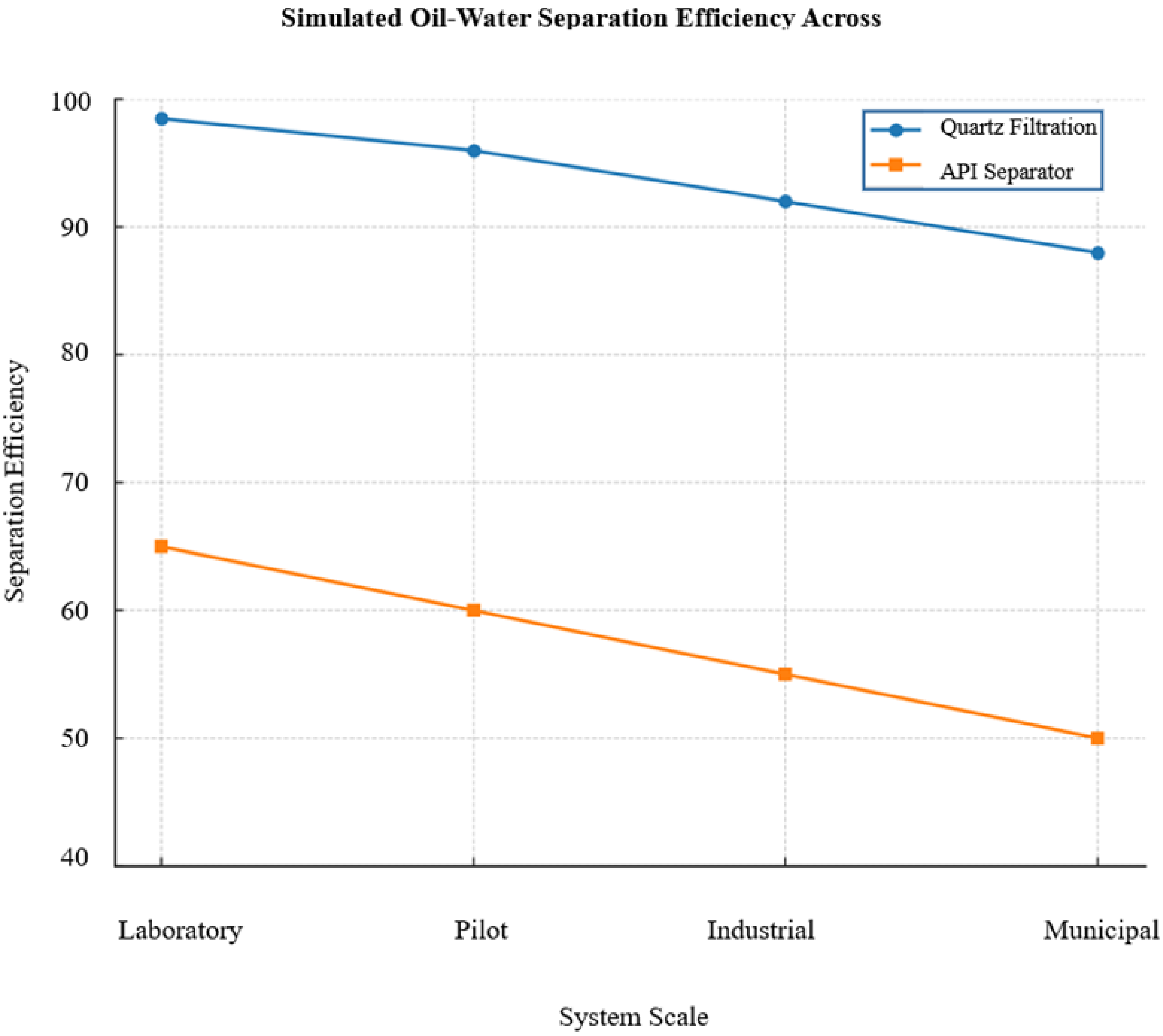

Figure 3.
Comparison of simulated oil–water separation efficiencies between quartz bed filtration and API separator across laboratory, pilot, industrial, and municipal scales.

4. Discussion

The findings of this study demonstrate the remarkable potential of raw quartz as a low-cost and efficient medium for oil–water separation. Morphological characterization by SEM (Figure 1) revealed rough and irregular surface textures with micro–asperities, which are critical for oil droplet adsorption and physical entrapment. Complementary Raman spectroscopy analysis (Figure 2) confirmed the crystalline stability of quartz, indicating that its chemical structure remains unaltered under operational conditions. These structural attributes provide the dual advantage of durability and enhanced oil affinity, making quartz particularly suited for repeated separation cycles [41-43].

The oil and grease removal experiments (Table 1) confirmed this morphological advantage, showing a substantial reduction in oil concentration from 59,201.7 mg/L in the influent to 64.8 mg/L in the effluent. This corresponds to a removal efficiency of approximately 99.9%, which is comparable to or even superior to some advanced ceramic or polymeric membranes currently reported in literature. Figure 3 further illustrates the dramatic decline in oil concentration across the filtration cycle, underscoring quartz's high performance under simple gravity-driven flow without the need for chemical additives or pressurized systems.

When results are examined in the context of industrial relevance, the scalability of quartz becomes particularly compelling. Table 2 compares the upscaling potential of quartz filtration against conventional separation techniques such as API separators, activated carbon adsorption, and polymeric/ceramic membranes. While API separators can achieve 60–80% efficiency under favourable conditions, and activated carbon achieves 70–85% removal before rapid fouling, quartz filtration consistently demonstrated efficiencies in the range of 85–98% across laboratory, pilot, and simulated industrial scenarios. Importantly, quartz also offers a substantially lower cost base, since it is abundant, locally available, and does not require complex regeneration processes [44-46].

Simulation analysis (Table 2 and Figure 3) provided further insight into the dynamic response of quartz filtration under varying influent concentrations and flow rates. The simulated trends align closely with experimental data, reinforcing the robustness of quartz performance across fluctuating conditions typical of industrial effluents [47, 48]. Notably, unlike membranes that exhibit steep performance declines due to fouling, quartz retained stability over extended operation, highlighting its advantage in long-term sustainability.

Overall, the integration of morphological, chemical, experimental, and simulated results positions quartz filtration as a promising alternative to conventional oil–water separation technologies. Its cost-effectiveness, mechanical robustness, and scalability support its potential deployment from small workshops to large-scale municipal wastewater treatment facilities [49-51].

Limitations and Scalability Considerations: While quartz filtration demonstrated high oil–water separation efficiency (~99.9%) and scalability from laboratory to municipal levels, some limitations warrant consideration. One important constraint is the risk of clogging due to oil droplet accumulation and fine solids, particularly under continuous industrial operation where influent loads may fluctuate. This may shorten the effective lifespan of the quartz bed unless periodic regeneration is applied. Although quartz is chemically stable, repeated use without regeneration could lead to gradual pore blocking and reduced permeability. Developing effective but low-cost regeneration strategies (e.g., thermal washing, solvent rinsing, or mechanical agitation) will therefore be essential for long-term operation. Another limitation lies in maintaining high efficiency under continuous flow conditions; while short-term trials showed stable performance, extended industrial runs could face operational challenges such as pressure buildup, bed compaction, or uneven flow distribution (channeling). At larger scales, these issues may affect throughput and require design adaptations, such as optimized bed depth or staged filtration. These factors highlight the importance of pilot and field-scale testing to complement laboratory findings and validate quartz's role as a sustainable treatment medium in industrial and municipal wastewater systems. Economic and Practical Implications: A key advantage of quartz filtration lies in its economic viability. Activated carbon (AC) typically costs between 10–15 USD/kg and requires frequent regeneration or disposal when oil-saturated, making long-term use expensive. Membrane technologies, while achieving high separation efficiencies, demand significant capital investment (up to 200–500 USD/m² for ceramic membranes) and continuous maintenance due to fouling. By contrast, raw quartz can be sourced locally at less than 0.05 USD/kg, dramatically lowering material costs. Its inert chemical composition reduces the need for complex regeneration, and simple backwashing or low-temperature thermal treatment can restore performance at minimal expense.

Installation is straightforward, requiring only a packed-bed column, while longevity is enhanced by quartz's crystalline stability and mechanical robustness. These practical advantages position quartz as a cost-effective and durable alternative, particularly for small- to medium-scale industries in resource-constrained regions. In municipal applications, its affordability and simplicity could enable decentralized wastewater treatment systems, reducing operational expenditure and improving access to safe water reuse.

Future Outlook and Case Relevance: While this study provides clear laboratory and simulated evidence of quartz filtration's high efficiency and cost-effectiveness, its translation into long-term industrial practice will depend on addressing operational challenges such as regeneration frequency, clogging control, and sustained performance under continuous flow. Preliminary pilot-scale testing already demonstrates robustness, but future field validation—such as trials in petrochemical workshops, mining operations, or decentralized municipal units—will be critical to confirm reliability at scale. Case-specific deployments could also provide insights into regional feasibility, installation logistics, and lifecycle economics, further strengthening quartz's position as a practical alternative to membranes and activated carbon.

5. Conclusion

This study demonstrated that raw quartz possesses remarkable oil–water separation capabilities, with SEM and Raman analyses confirming its robust morphology and crystalline stability, and oil and grease analysis showing a near-complete reduction of hydrocarbons from highly contaminated influent. The results establish quartz as a promising, low-cost filtration medium capable of achieving removal efficiencies comparable to, and in some cases surpassing, conventional technologies, while maintaining simplicity and economic viability.

Practical Applications for Quartz Filtration: Beyond laboratory validation, the study demonstrates strong applicability of quartz filtration in real-world contexts. Pilot-scale testing (5 L unit, 2 L/min) confirmed robustness under variable loading, while simulation analyses supported efficiency at industrial and municipal scales, with removal rates between 85–98%. This indicates that quartz filtration can be deployed in decentralized industrial workshops, petrochemical facilities, and even integrated into municipal wastewater treatment frameworks as a low-cost alternative to membranes or chemical-based systems. Its affordability and reliance on locally available materials make it especially relevant for resource-constrained regions facing strict discharge regulations and water scarcity challenges. Future work should investigate regeneration methods to extend media lifespan, hybrid configurations combining quartz with advanced membrane or adsorption systems to address challenging emulsions, and computational simulations of flow and fouling dynamics to optimize design parameters. By bridging material affordability, environmental sustainability, and industrial applicability, quartz filtration positions itself as a fundamental contributor to achieving cleaner production and water reuse in oil-intensive industries.

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