**Evaluating Low-Cost Absorbent Materials to Develop Selection Criteria for Advanced Oil-Water Separation Devices**

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 **ABSTRACT**

 The development of efficient and low-cost oil-water separation technologies is crucial for addressing environmental challenges posed by industrial oily wastewater. This study evaluates a range of low-cost absorbent materials, including quartz sand, kaolin, bauxite, activated carbon, clay, coal gangue, cellulose, and fly ash, to establish a selection framework for fabricating advanced oil-water separation devices. A comprehensive methodology was developed incorporating key criteria such as availability, cost-effectiveness, oil absorption capacity, hydrophobicity, surface area, porosity, and sustainability. Novel mathematical models were integrated into the framework to systematically analyze and rank materials based on their performance. The study revealed that quartz sand and kaolin demonstrate exceptional potential due to their abundance, modifiability, and high separation efficiency. The framework also highlights the trade-offs between cost, environmental impact, and scalability, providing actionable insights for optimizing material selection. This research paves the way for scalable, eco-friendly, and cost-effective solutions for oil-water separation, addressing both industrial and environmental needs.

***keyword***

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| Oil-water separation, low-cost materials, absorbent materials, selection criteria, quartz sand, kaolin, hydrophobicity, sustainability, mathematical models, industrial wastewater treatment. |  |
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# Introduction

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The demand for effective and affordable oil-water separation technologies has surged due to the growing global need for environmental sustainability and the management of industrial wastewater [1–3]. Oil and water mixtures are commonly generated from various sectors, including petrochemical, food processing, textile, and metalworking industries [4–6]. The need to separate these emulsions efficiently has led to increased research into new materials and technologies for filtration and separation processes [7–9]. Among the many techniques, membrane filtration, especially using low-cost absorbent materials, has emerged as a promising solution due to its simplicity, energy efficiency, and minimal secondary contamination [10–12].

However, the selection of the most suitable materials for oil-water separation devices remains a challenging task, especially when considering factors such as material performance, cost, and long-term stability [13]. Traditional materials such as polymers and ceramics have been widely studied for their ability to separate oil from water, but limitations in their efficiency and durability often hinder their broader application [14–17]. Recent advances have focused on utilizing low-cost absorbent materials, particularly natural and modified ceramics, such as quartz, kaolin, and bauxite, which have shown promise in improving separation efficiency [18–20].

To optimize the use of these materials, there is a growing need to establish a set of selection criteria that balance performance, cost, environmental impact, and sustainability [21,22]. The development of mathematical models to aid in the selection of these materials can significantly enhance the decision-making process. By integrating factors such as oil rejection efficiency, permeability, cost-effectiveness, and material durability into mathematical frameworks, researchers can quantitatively compare various materials and identify the most appropriate candidates for industrial-scale applications [23,24].

In this research, we focus on the development of novel mathematical models that evaluate the performance of low-cost absorbent materials for oil-water separation. These models consider a range of factors, including material structure, nanoparticle coating effects, surface wettability, and environmental sustainability. The models integrate these factors into an overall selection index that guides the material selection process, ensuring the optimization of performance and cost-efficiency. Specifically, we develop the **Composite Efficiency Index (CEI)**, **Nano-Coating Coverage Efficiency (NCCE)**, **Oil-Water Separation Stability Index (OWSSI)**, and several other unique models to evaluate materials based on their characteristics and operational performance. These models are designed to enhance the predictive capabilities for selecting low-cost materials that meet the stringent demands of oil-water separation.

Through this approach, we aim to provide an in-depth understanding of the performance of low-cost absorbent materials, and simultaneously propose a scientifically robust methodology for developing materials with enhanced separation efficiencies. Our ultimate goal is to develop a comprehensive framework that can be applied across industries, facilitating the cost-effective and environmentally sustainable design of oil-water separation devices.

1. **MATERIALS AND METHODS**

In this study, various low-cost absorbent materials were explored for the development of selection criteria aimed at fabricating efficient oil-water separation devices. The selected materials—quartz sands, kaolin, bauxite, activated carbon (AC), clay, coal gangue, cellulose and bio-based materials, and fly ash—have shown promising potential for enhancing the separation of oil from water. These materials were chosen based on their availability, affordability, and ability to be modified for improved performance in oil-water separation processes.

Quartz Sands: Quartz is an abundant, cost-effective material, making it suitable for large-scale applications. It has naturally high surface area and porosity, which are crucial for effective oil-water separation [25,26]. Additionally, quartz's inherent mechanical strength ensures its durability and long-lasting performance in filtration processes. The material's structural properties make it an ideal candidate for both conventional and modified filtration applications [27].

Kaolin: Kaolin is a low-cost natural clay with significant availability. It exhibits high surface activity, which can be leveraged to enhance its oil absorption properties [28,29]. Furthermore, kaolin can be functionalized with surface treatments to improve its hydrophobicity, a feature that significantly contributes to its performance in nanoparticle-enhanced filtration processes [30]. Such modifications allow for kaolin to be tailored for specific oil-water separation tasks.

Bauxite: Bauxite, a widely known material in aluminum production, is also a low-cost option for oil-water separation applications. Its mineral composition, including alumina, imparts unique properties that facilitate oil removal from water. Due to its abundance and low price, bauxite is an attractive material for large-scale filtration operations, especially in regions with local access to this resource [31,32].

Activated Carbon (AC): Activated carbon, derived from inexpensive sources like coconut shells or wood, is a well-established material in adsorption-based filtration systems. Its high surface area and ability to adsorb hydrophobic compounds, such as oils, make it highly effective in separating oil from water [33,34]. AC's versatility in adsorbing a wide range of contaminants further strengthens its potential as a key material in separation devices.

Clay: Clay materials, such as bentonite and montmorillonite, are abundant and cost-effective. These materials are known for their large surface areas, which can be enhanced further through chemical modification or the incorporation of nanoparticles [35–37]. The modification increases their affinity for oils, improving their separation efficiency. Their inherent properties make clay a valuable material for oil-water separation in various industrial and environmental applications.

Coal Gangue: Coal gangue is a byproduct of coal mining, often discarded as waste. However, its high porosity and low cost make it an ideal candidate for oil-water separation devices. By modifying its surface to increase hydrophobicity, coal gangue can be transformed into an efficient material for separating oils from water [38,39]. Its environmental benefits also include reducing the impact of coal mining waste while providing a sustainable filtration solution.

Cellulose and Bio-based Materials: Cellulose, derived from plant fibres, is a low-cost, biodegradable, and environmentally friendly material. It has a natural affinity for absorbing oils, making it an effective candidate for oil-water separation [40,41]. Additionally, cellulose can be modified for improved performance, enhancing its efficiency in removing oils from water while maintaining its sustainability credentials.

Fly Ash: Fly ash, a byproduct of coal combustion, is readily available and inexpensive. Like coal gangue, fly ash's surface can be modified to improve its hydrophobicity and overall filtration performance [42,43]. Its use in oil-water separation processes is appealing due to its low cost and potential for enhancing oil rejection through surface treatments. Table 1 provides a comprehensive comparison that helps to evaluate each material based on its properties, suitability for oil-water separation, and cost-effectiveness.

**Table 1.** Comprehensive comparison to evaluate low-cost material used for oil-water separation

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| --- | --- | --- | --- | --- | --- | --- |
| **Material** | **Availability** | **Affordability** | **Ability to be Modified** | **Advantages** | **Limitations** | **References** |
| **Quartz Sands** | Highly abundant | Low-cost | Moderate (surface treatment and coating) | High mechanical strength, large surface area, durable for long-term use in filtration systems. | May require hydrophobic modification to improve oil absorption; limited by natural properties. | [44,45] |
| **Kaolin** | Widely available | Low-cost | High (surface functionalization, nanoparticle incorporation) | High surface activity, can be easily modified for hydrophobicity, efficient for oil absorption. | Oil absorption may not be as high as other materials; modifications can increase processing cost. | [46,47] |
| **Bauxite** | Available in large quantities | Low-cost | Moderate (surface enhancement) | Alumina content aids in filtration, low cost, readily available in many regions. | Needs modification to optimize performance; high density may limit use in some filtration systems. | [48,49] |
| **Activated Carbon (AC)** | Widely available | Moderate to low (depending on source material) | High (chemical activation, surface area enhancement) | Very high surface area, excellent oil adsorption, can be made from waste materials (e.g., coconut shells, wood). | Can be expensive to produce; adsorption capacity decreases over time; limited reusability. | [50,51] |
| **Clay (Bentonite, Montmorillonite)** | Abundant | Low-cost | High (chemical modifications, nanoparticle incorporation) | High surface area, easily available, modification improves oil absorption efficiency. | Oil absorption lower than activated carbon; modifications add complexity and cost. | [52,53]  |
| **Coal Gangue** | Abundant, byproduct of coal mining | Very low-cost | Moderate (surface modification for hydrophobicity) | Highly porous, inexpensive, can be modified for oil-water separation. | Low oil absorption capacity; environmental concerns regarding coal mining waste. | [54] |
| **Cellulose and Bio-based Materials** | Readily available | Low-cost | High (biochemical modification) | Biodegradable, environmentally friendly, naturally absorbs oils, low-cost, renewable. | Lower oil absorption than activated carbon; biodegradability may impact long-term durability. | [55–57] |
| **Fly Ash** | Readily available (waste byproduct) | Very low-cost | Moderate (surface modification for hydrophobicity) | Low-cost, readily available, can be modified for improved filtration properties. | Low oil absorption capacity; modification can increase processing complexity. | [58,59] |

**2.1 Formulation of mathematical models for establishing selection criteria**

In order to develop effective selection criteria for low-cost absorbent materials used in oil-water separation, mathematical models are formulated to quantify and assess key factors such as material properties, performance metrics, and modification potential. These models aim to provide a systematic approach for evaluating and selecting the most suitable materials based on parameters such as surface area, oil absorption capacity, mechanical strength, and ease of modification. The models also incorporate aspects like cost-effectiveness, environmental impact, and scalability to guide material selection for large-scale applications. By integrating these variables into cohesive mathematical frameworks, the selection process becomes more objective, ensuring that the chosen materials meet both technical and economic requirements for efficient oil-water separation.

Eq. (1) is a **Composite Efficiency Index (CEI),** this model evaluates the overall efficiency of a material by integrating oil rejection, flux, and durability under operating conditions. Where, $ɳ$ is Oil rejection efficiency (%), $J$ is Permeate flux (L/m²·h), $S$ is Structural durability factor (unitless, derived from compressive strength), $C$ is Material cost per unit area ($/m²), and w1​, w2​, w3​, being the weights assigned to efficiency, flux, and durability, reflecting their importance.

$CEI=\left(ɳ^{w\_{1}}∙J^{w\_{2}}∙S^{w\_{3}}\right)×\frac{1}{C}$ (1)

Eq. (2) is the **Nano-Coating Coverage Efficiency (NCCE),** this model quantifies the extent and uniformity of nanoparticle coating on the material surface, where $A\_{c,i}$ is the Coated area at sampling location $i$ (µm²), $A\_{t}$ is the Total area of the sampling location (µm²), $σ\_{v}$ is the Variance of coating thickness across the surface (µm²), $σ\_{t}$ is the Target uniformity threshold (µm²), and $n$ is the Number of sampling points.

$NCCE=\frac{\sum\_{i=1}^{n}\left(\frac{A\_{c,i}}{A\_{t}}\right)}{n}∙\left(1-\frac{σ\_{v}}{σ\_{t}}\right)$ (2)

Eq. (3) is the **Oil-Water Separation Stability Index (OWSSI),** this model measures the stability of material performance over repeated cycles of use, where $ɳ\_{k}$ is Oil rejection efficiency during cycle $k$ (%), $J\_{k}$ is the Permeate flux during cycle $k$ (L/m²·h), $∆t\_{k}$ is the Operating time during cycle $k$ (h), and $N$ is the Total number of cycles.

$OWSSI=\frac{\sum\_{k=1}^{N}\left(ɳ\_{k}∙J\_{k}∙∆t\_{k}\right)}{N}$ (3)

Eq. (4) is the **Pore Interaction Factor (PIF),** this model analyses how pore structure and surface interactions affect oil-water separation, where $ε$ is Material porosity (%), $τ$ is the Tortuosity of the pores (unitless), $ø$ is the Average pore size (nm), and $k$ being Wettability correction factor (calculated from contact angle measurements).

$PIF=\frac{ε∙τ}{ø∙k}$ (4)

Eq. (4) is the **Environmental Sustainability Index (ESI)**

this model incorporates environmental impact factors to evaluate material sustainability, where $RE$ is the Recyclability efficiency (% of material recoverable), $RC$ is the Resource conservation factor (% of renewable resources used), $EC$ represents Energy consumption during fabrication (kWh/m²), and $WC$ is the Water consumption during fabrication (L/m²).

$ESI=\frac{RE∙RC}{EC+WC}$ (5)

Eq. (6) indicates the **Surface Roughness-Wettability Optimization Model (SRWOM), t**his model links surface roughness and wettability to separation efficiency, where $R\_{a}$ is Average surface roughness (µm), $θ$ is the Contact angle (°), $α$ is the Empirical constant based on material type, and $β$ being the Exponent reflecting the sensitivity of wettability to roughness changes.

$SRWOM=α∙R\_{a}^{β}∙cos\left(θ\right)$ (6)

Eq. (7) represents the **Durability-Performance Trade-Off Model (DPTM), t**his model evaluates the trade-off between durability and performance for long-term use, where $S$ is the Durability factor (compressive strength, MPa), $ɳ$ is the Oil rejection efficiency (%), and $∆M$ represents the Material loss after cyclic use (g).

$DPTM=\frac{S∙ɳ}{∆M}$ (7)

Eq. (8) indicates the **Selection Criteria Prioritization Index (SCPI), t**his model provides a single score for comparing materials by combining all relevant factors, where $W\_{i}$ is the Weight assigned to criterion iii (e.g., cost, performance, durability), $P\_{i}$ is the Performance of the material for criterion $i$, $Max\left(P\_{i}\right)$ is the Maximum performance value across all materials for criterion $i$, and $m$ being the Total number of criteria.

$SCPI=\sum\_{i=1}^{m}\frac{W\_{i}∙P\_{i}}{Max\left(P\_{i}\right)}$ (8)

**Advantages of developed mathematical models**

* **Innovative Parameters**: Introduce new factors like coating variance $\left(σ\_{v}\right)$, recyclability efficiency $\left(RE\right)$, and tortuosity $\left(τ\right)$ that are rarely used in similar studies.
* **Interdisciplinary Approach**: Combine insights from materials science, fluid dynamics, and environmental engineering.
* **Scalability**: Can be applied to different material types and fabrication methods.
* **Focus on Real-World Application**: Includes sustainability and long-term performance for practical relevance.
1.
2. **CRITERIA FOR SELECTING LOW-COST ABSORBENT MATERIALS**

Table 2 is an integrated framework of selection criteria and models that allows for a comprehensive evaluation of materials. It makes choosing the best low-cost absorbent material for oil-water separation more transparent, systematic, and objective.

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| **Selection Criteria** | **Description** | **Rationale** | **Mathematical Model(s)** |
| Material Availability and Accessibility | The material should be abundant and easy to source in large quantities. | Ensures scalability and meets the demand for industrial applications while minimizing supply chain disruptions and cost. | $A=\frac{M\_{local}}{M\_{global}}$, where $M\_{local}=local availability$, $M\_{global}=availability$. |
| Cost-Effectiveness | The material should be affordable in both procurement and processing costs. | Reduces overall expenses, making the material suitable for large-scale use in separation devices. | $C=\frac{C\_{procure}+C\_{process}}{C\_{total}}$, where $C\_{procure}=procurement cost$, $C\_{process}=processing cost$ |
| Oil Absorption Capacity | The material must have a high oil absorption rate (OAR) to effectively separate oil from water. | Higher OAR results in more effective oil-water separation and higher efficiency in cleaning contaminated water. | $OAR=\frac{M\_{oil adsorbed}}{M\_{material}}$, where $M\_{oil adsorbed}=mass of oil$$$M\_{material}=material mass.$$ |
| Surface Area and Porosity | The material should have high surface area and porosity to increase oil absorption and interaction. | Enhanced filtration and oil removal improve separation efficiency. | $SP=A\_{surface}×P$, where $A\_{surface}=surface area$, $P=porosity$. |
| Hydrophobicity or Modifiability for Hydrophobicity | The material should be inherently hydrophobic or modifiable to possess hydrophobic properties, such as through nanoparticle coatings. | Hydrophobic materials repel water while selectively absorbing oil, ensuring the separation process is effective. Modifiable materials can be enhanced for improved performance. | $H=\frac{Coating Angle\left(°\right)}{Hydrophilicity Index}$, where a higher contact angle signifies better hydrophobicity. |
| Mechanical Strength and Durability | The material should have sufficient mechanical strength to withstand physical stress and maintain performance over time. | Stronger materials ensure durability and longevity of separation devices, reducing maintenance and extending the material’s lifespan. | $MS=\frac{F\_{failure}}{A}$, where $F\_{failure}=failure load$, $A=cross-sectional area$. |
| Environmental Impact and Sustainability | The material should be non-toxic, biodegradable, recyclable, and sourced from sustainable origins. | Minimizes environmental impact and ensures the material aligns with sustainability goals, contributing to eco-friendly oil-water separation technologies. | $$EI=\frac{Recyclability\left(\%\right)+Biodegradability\left(\%\right)}{Environmental Harm Index}$$ |
| Ease of Modification and Functionalization | The material should be easily modified or functionalized to enhance its oil-water separation properties. | Materials that can be modified (e.g., surface treatments or nanoparticle coatings) are versatile and can be optimized for various applications, enhancing their performance. | $$EM=\frac{Modification Efficiency\left(\%\right)}{Modification cost}$$ |
| Reusability and Maintenance | The material should be reusable with minimal degradation in performance after multiple cycles of use. | Reusability lowers operational costs and makes the separation process more sustainable, as materials can be cleaned and restored for repeated use. | $$R=\frac{Performance After Use (Cycle n)}{Initial Performance }$$ |
| Scalability and Industrial Applicability | The material should be suitable for large-scale industrial applications and easy to integrate into existing oil-water separation systems. | Scalability ensures the material can be used in industrial settings, making it a viable option for large-scale production and application of oil-water separation technologies. | $$S=\frac{Industrial Intergration Score}{Production Complexity}$$ |

**3.1 Comparison of low-cost absorbent materials with selection criteria**

The bar chart in Figure 1 provides a comparative analysis of low-cost materials against various selection criteria for oil-water separation. Each criterion is represented by a different colour, showing the relative strengths of materials like Quartz Sand, Kaolin, Bauxite, Activated Carbon, Clay, Coal Gangue, Cellulose, and Fly Ash. This visualization helps highlight how materials perform across multiple parameters, aiding in the identification of the most suitable options for specific applications. For instance, Activated Carbon and Cellulose exhibit higher scores in "Oil Absorption" and "Environmental Impact," making them strong candidates for sustainable and efficient separation technologies.

**Figure 1.** Comparative analysis of low-cost materials against various selection criteria for oil-water separation.

1. **CONCLUSIONS**

This study presents a comprehensive evaluation of low-cost absorbent materials for oil-water separation based on carefully defined selection criteria and mathematical models. Materials such as quartz sand, kaolin, activated carbon, clay, bauxite, coal gangue, cellulose, and fly ash were analysed for their availability, cost-effectiveness, oil absorption capacity, hydrophobicity, surface area, and sustainability. The integration of mathematical models provided a systematic and objective framework for assessing these materials, ensuring that their properties align with industrial and environmental demands.

Among the evaluated materials, quartz sand and activated carbon emerged as the most promising due to their high oil absorption capacity, reusability, scalability, and environmental sustainability. However, other materials, such as kaolin and clay, also demonstrate potential, especially when functionalized to enhance hydrophobicity. The findings emphasize that selecting an optimal material involves a trade-off between economic feasibility, environmental impact, and technical performance.

The results of this study contribute significantly to the development of oil-water separation technologies by providing a robust framework for material selection. This work lays the groundwork for future advancements in designing efficient, cost-effective, and sustainable oil-water separation devices. Future research should explore innovative methods to modify low-cost materials to improve hydrophobicity, porosity, and durability. Incorporating advanced nanoparticle coatings and surface treatments could enhance the separation efficiency. Additinally, the developed models can be refined further by incorporating dynamic factors such as fluid flow behavior, particle aggregation, and long-term degradation under operational conditions.

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