

DEVELOPMENT OF ALUMINA HOLLOW FIBER MEMBRANE MODULES FOR EFFECTIVE OIL/WATER SEPARATION

ABDULLAH, N.^{1,2} – PARAMASIVAM, H.¹ – HUA, A. K.^{3*}

¹ *Nanomaterials Research Centre, Universiti Malaysia Sabah, Sabah, Malaysia.*

² *Faculty of Engineering, Univeristi Malaysia Sabah, Sabah, Malaysia.*

³ *Faculty of Arts and Social Sciences, University of Malaya, Kuala Lumpur, Malaysia.*

**Corresponding author
e-mail: angkeanhua888[at]um.edu.my*

(Received 08th May 2025; revised 10th August 2025; accepted 20th August 2025)

Abstract. This study critically engages with the context of increasing industrial and urban wastewater challenges where an effective oil-water separation process is considered. In most cases, the traditional gravity separator and centrifuge fail to isolate stable small droplets of oil from water in emulsified form. Alumina hollow fiber membrane modules that this study has undertaken fabrication efforts toward are proposed as one more step further to solve this problem. The hydrophobicity enhanced system shows all promises towards effectively carrying out the separation of oil from water in emulsions. Different membrane configurations tried possible relationships that this work presents between changing the number of membranes and efficiency in separation. Increasing surface area, i.e., an increasing number of fibers, allows more oil recovery but at a cost since fouling will tremendously take place. Even though the membrane could achieve very high separation efficiency, challenges related to operation, especially fouling at high concentrations of oil and the effects due to different flow rates have to be solved when applied on an industrial scale. This brings out the study's view that getting sustainable, cheap, and efficient ways of carrying out the oil-water separation process necessitates the optimization of membrane configurations and operating conditions.

Keywords: *alumina membranes, oil-water separation, hollow fiber modules, membrane technology, wastewater treatment*

Introduction

The rise in industrial and urban expansion has led to the generation of large volumes of oily wastewater, posing a significant threat to global water security and environmental sustainability. Conventional oil-water separation techniques such as gravity separation, centrifugation, and hydrocyclone systems have limitations in efficiency, energy consumption, and secondary contamination (Nasiri et al., 2017). As alternative, membrane-based technologies, particularly hollow fiber membrane systems, offer compact, cost-efficient, and eco-friendly solutions for the treatment of oily wastewater (Mousa et al., 2022). Alumina-based hollow fiber membranes are particularly suitable due to their robustness, high thermal and chemical resistance, and superior permeability characteristics. These ceramic membranes are designed to allow oil to permeate while rejecting water, achieving efficient phase separation through hydrophobic modifications. Recent studies have demonstrated promising results in treating emulsified oil-water mixtures using modified ceramic membranes, with particular focus on membrane hydrophobicity, structural design, and operational flowrate (Wei et al., 2024; Baig et al., 2022). This study focuses on the development of

an alumina hollow fiber membrane module with various configurations for enhanced oil-water separation.

Environmental degradation from oily wastewater discharge remains a pressing global issue, particularly within oil and gas industries and urban wastewater systems. Over 250 million barrels of oily wastewater are produced daily in oil fields, with a significant portion released untreated into natural ecosystems (Liu et al., 2019). In many developing regions, this challenge is exacerbated by inadequate infrastructure and outdated technologies. Traditional separation methods are inadequate, especially for emulsified oil, which presents smaller droplet sizes and higher stability, rendering them difficult to isolate using gravity-based techniques alone (Gupta et al., 2017). Moreover, chemical demulsification, though effective, often results in secondary pollution and increased operational costs (Nour et al., 2007). Consequently, industries are actively seeking separation technologies that are environmentally sustainable, scalable, and economically feasible. The alumina hollow fiber membrane presents a viable alternative with its high surface area, mechanical durability, and hydrophobic behavior when modified with fluorine-based polymers. However, little is known about the influence of different module configurations, such as the number of fibers, on separation efficiency. This gap necessitates targeted research to determine optimal membrane designs and operational parameters that can maximize oil recovery while ensuring water purity.

The global concern surrounding oil spill incidents and their environmental repercussions has intensified research into innovative oil-water separation technologies. Oil spill disasters, such as those reported by the International Tanker Owners Pollution Federation (ITOPF), release tens of thousands of gallons of crude oil into marine ecosystems annually (Chen et al., 2019). These spills have devastating effects on aquatic biodiversity, coastal economies, and human health. Traditional cleanup approaches such as skimmers and absorbents are often inefficient under turbulent conditions. Bioinspired designs, such as superhydrophobic surfaces mimicking lotus leaves, have shown potential in advancing separation methods (Liu et al., 2013). Such surfaces repel water while attracting oil, a principle central to the membrane technology employed in this study. Membrane separation technologies have emerged as a highly promising alternative for oily wastewater treatment due to their efficiency, compactness, and environmental compatibility. Unlike conventional chemical treatments, membranes offer selective separation based on pore size and surface affinity (Ahmad et al., 2020). Ultrafiltration, microfiltration, and nanofiltration membranes are commonly used, with ceramic materials such as alumina offering added advantages like thermal stability and fouling resistance (Baig et al., 2022). Notably, hollow fiber membranes possess high packing density and a self-supporting structure, allowing large surface areas in compact module volumes (Baker, 2023). Park et al. (2012) emphasize that membrane technology's modular design enables scalable deployment, making it suitable for both centralized and decentralized water treatment systems. The use of fluorine-modified alumina hollow fiber membranes represents an innovation capable of enhancing hydrophobicity, facilitating superior oil-water separation performance even under challenging conditions.

The overarching aim of this research is to design and assess an alumina hollow fiber membrane module capable of efficiently separating oil from water in emulsion systems. This aim is achieved through three specific objectives: (1) to design and fabricate a membrane module using varying numbers of alumina hollow fiber membranes; (2) to investigate the effect of membrane quantity on oil recovery efficiency; and (3) to

evaluate the separation performance of the module under varying oil concentrations and flowrates. These objectives are framed to provide insights into optimal membrane configurations and operating conditions necessary for practical deployment in industrial wastewater treatment facilities.

Literature review

The obvious and continuous existence of oil spills and oily wastewater in the world environment aptly reflects the anomaly of modern industrial development. With all technological advancements, remediation practices have not become transformative enough. Practically, the earlier effective separation methods by gravity settling, centrifugation, or chemical demulsification have now exposed their practical limitations, hence proving inadequacies at a systemic level. For instance, these often prove ineffective in dealing with fine droplet emulsions below 20 μm ; such droplets are increasingly present within petrochemical effluents and offshore spills (Abuhasel et al., 2021). Chemical dispersants, which reduce interfacial tension thus promoting easier breakup of droplets onto surfaces also happen to be environmentally unfriendly as they leave toxic residues that are not biodegradable (Adofo et al., 2022). This sets up a net contradiction in which methods that reduce visible short-term pollution actually increase long-term ecological damage. In addition, such energy-intensive treatment running parallel to the generation of secondary wastes is fundamentally misaligned on the very lines of treatment with global sustainability targets. This contradiction has led to a new paradigm, where research focus is not only on “removal efficiency” but on integrated solutions that can achieve ecological compatibility, energy minimisation, and adaptability in different water chemistries. To reframe it, there is a need for technologies that go beyond being just remedial to becoming transformative and put membrane science at the heart of environmental innovation.

Membrane technologies are increasingly perceived not as incremental advancements but rather as potential disruptive alternatives. In some instances, the general view in the industry is that nanostructured and biomimetic enhanced membranes. Selectivity and scalability is enabled by using tunable membranes with significantly reduced chemical usage compared to conventional systems. Two forces slow down innovation: increasing efforts toward a real breakthrough on one hand and even more toughened criteria for applicability on the other hand. Ceramic membranes, e.g., alumina, have unmatched and unchallenged high-pressure stability and high-temperature stability; thus, theoretically attractive for industrial effluents where polymeric membranes cannot perform membrane fabrication costs remain prohibitively high. Hence, membrane fouling still undermines the long-term efficiency of any membrane regardless of type or material used. Likewise, bioinspired approaches - sunflower leaf-derived SnO_2 coatings (Li et al., 2020) reconcile high performance with environmental responsibility by eliminating toxic reagents. However, it is essential to note that although laboratory breakthroughs are increasingly being achieved, their industrial translation remains limited due to issues of scalability, cost, and complexity of operation. Therefore, the question is not whether or not membranes can separate oil from water-they demonstrably can-but whether they can do so at the required scales of affordability and reliability as well as sustainability that the industry demands.

The intersection of material innovation, process integration, and intelligent system management is where the frontier of oil–water separation happens now. That is also where some unresolved limitations keep provoking debate. Fouling remains the

Achilles' heel of membrane systems with flux reduction by oil, surfactants, and suspended solids adding to costs long before any advances in wettability engineering could ever decrease these effects to a minimum degree (Xiang et al., 2022). Xiang et al. (2022) points out another reason for failure: most laboratory-optimized superhydrophobic or oleophobic membranes fail miserably in changing field conditions hence proving how frail performance claims under controlled laboratory settings are. Even more telling about this problem are revealed research trajectories: one camp pursues it as a classic material science problem, new coatings; the rest take it further by hybridizing between membrane systems and adsorption, electrochemical, or catalytic pre-treatments thereby extending the horizon further operationally (Coca-Prados et al., 2012). More and more computational tools and artificial intelligence are entering the field, not only to predict fouling dynamics but optimising parameters in real time thus implying that digitalisation may have something to do with laboratory design coming into contact with industrial resilience. However, on closer reading the literature has posed an unresolved dilemma: though membranes are considered sustainable, high costs of advanced ceramics, nanomaterials, and hybrid modules may usher in a technology which is ecologically progressive yet economically exclusionary. The implied message is rather loud unless cost, durability, and adaptability issues are addressed simultaneously; consequently meaning mainstreaming will be stalled notwithstanding experimental success. It therefore calls for holistic frameworks integrating materials, processes, and management systems delivering oily wastewater treatment that is technically superior as well as socio-economically viable.

Materials and Methods

This project adopted three major phases in its methodology: preliminary work, fabrication of the prototype, and testing of the prototype. In the initial phase, designs of existing membrane modules were reviewed considering design limitations as well as strength and cost-effectiveness. Selection was made for a simple alumina hollow fiber membrane module due to low cost and separation capability for oil-water mixtures. This fulfilled Objective 1: To design and develop an alumina hollow fibre membrane module. The prototype membrane module was fabricated in the second stage. The alumina hollow fiber membrane module has been fabricated as per the initial design, creating three different types of modules: Module A (Single Membrane), B (Double Membrane), and C (Triple Membrane). It falls under objective 2 which is to study the effect a number of alumina hollow fiber membranes have for oil/water separation. At last, in this third stage, oil-water emulsions with different concentrations were run through the fabricated prototypes at varied operating conditions-specifically flow rate and number of membranes involved. Separation efficiency was obtained and analyzed, thus meeting Objective 3: To examine the oil/water separation using the alumina hollow fibre membrane module (*Table 1*).

Table 1. Materials and equipment used for fabrication of alumina hollow fiber membrane module.

| No | Item | Quantity |
|----|------------------------------------|----------|
| 1 | 8 cm alumina hollow fiber membrane | 6 |
| 2 | Fluorine-type polymer | 20 ml |
| 3 | Clear hose pipe | 2 meters |
| 4 | Aquarium water pump | 1 |

| | | |
|----|-------------------------------|---------|
| 5 | Oil-water emulsion | 1 litre |
| 6 | 7 cm transparent acrylic tube | 3 |
| 7 | Epoxy glue | 2 |
| 8 | Beaker | 1 |
| 9 | Transparent container | 1 |
| 10 | Measuring cylinder | 1 |

Preparation and testing of alumina hollow fiber membrane module

To determine the hydrophobicity of the alumina hollow fiber membranes, the contact angle was measured according to standard procedures. The cutting of the alumina hollow fiber membranes was first done to a length of 8 cm and later coated with a fluorine-type polymer material, thereby enhancing their hydrophobic properties. Lying horizontally on a holder, 1 μL water is dispensed by a syringe onto them. The contact angle is determined using Biolin Scientific software results which interpreted the value obtained to mean how hydrophobic that particular membrane material is. This test made sure that those alumina hollow fiber membranes were hydrophobic enough for oil-water separation applications. Once confirmed, those fabricated membranes have been used in further experimental tests (*Figure 1*). After the hydrophobicity tests, membrane modules A, B, and C were set up. Module A had one alumina hollow fiber membrane. Module B had two membranes and Module C used three membranes. These modules helped check how changing the number of membranes affects the oil-water separation result. An aquarium water pump linked to each module sent the feed solution (oil-water mix). The emulsion passed through the membrane, then permeate (oil) was caught and measured for more checks. The performance of these modules was seen under different test setups like various oil amounts and flow speeds to find the separation result for each setup (*Figure 2*).



Figure 1. Alumina hollow fiber membrane module A: A single membrane.



Figure 2. Alumina hollow fiber membrane module B (with two membranes).

Preparation of oil/water emulsion

The oil-water emulsion used in this study was representative of realistic industrial effluents that would be used to test the alumina hollow fiber membrane modules' separation performance. Three different oil percentages: 30%, 50%, and 70%; were prepared to test the membrane's efficiency against different types of content. For 70 ml water, 30 ml palm oil were mixed with surfactant (liquid soap) so that emulsion for 30% concentration could be stabilized. Similarly, for getting a 50% concentration, 50 ml water and 50 ml oil were mixed together; for a 70% concentration, 30 ml water and 70 ml oil were combined. Surfactants are required so that the mixture of oil and water remains in stable emulsion form because this is the typical problem found during studies about oil-water separations. The stability of emulsion is very critical towards obtaining results that may be reliable as well as reproducible during testing (*Figure 3*).

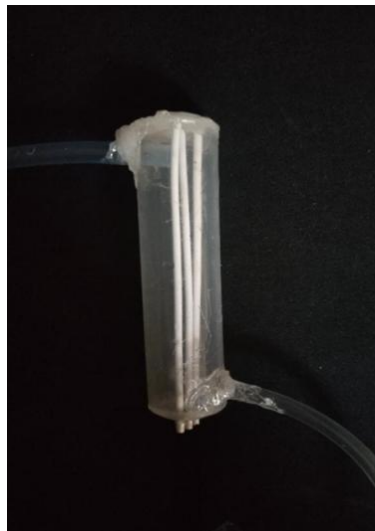


Figure 3. Alumina hollow fiber membrane module C (three membranes).

Lumina hollow fiber membrane module testing

The experimental setup involved pumping the prepared emulsion using alumina hollow fiber membrane modules for an efficiency test of oil-water separation. The A, B, and C membrane modules were connected to the aquarium water pump so that the flow of the oil-water emulsion through the membrane system would be facilitated. Permeate, which in this case is separated oil, was collected in a transparent container, and its volume recorded as a basis for evaluating efficiency. Testing was also repeated under different operating conditions for each membrane module to include varying flow rates and percent concentrations of oil in order to assess how membrane configuration affects separation processes. This will clearly bring out details concerning differences in separation efficiency between configurations-single, double, and triple membranes- thereby giving due consideration towards optimal configuration for efficient oil-water separation (*Figure 4*).



Figure 4. Setup for alumina hollow fiber membrane module experiment.

Results and Discussion

The first aim of this work was to design and develop an alumina hollow fiber membrane module casing in such a way that it could support the efficient separation of oil and water from their emulsion. The steps taken toward achieving this objective started with rough sketching moving on gradually to prototype development by exact design using AutoCAD. Some limitations, like inadequate surface area for providing efficient separation were present in the first design. These were overcome in the second version of the design, which gave a module having all the necessary physical requirements for carrying out oil/water separation. Material ordering has been done locally and internationally online because not all components are available in local shops. Despite the long wait for deliveries from overseas, work still went on, and the prototype was fully mounted within two weeks. It was very easy to build up the alumina hollow fiber membrane module with hand and power tools; indeed, it was this same module that was tested for oil-water separation. The setup used here is the one shown there as *Figure 5* presenting laboratory disposition of alumina hollow fiber membrane module.

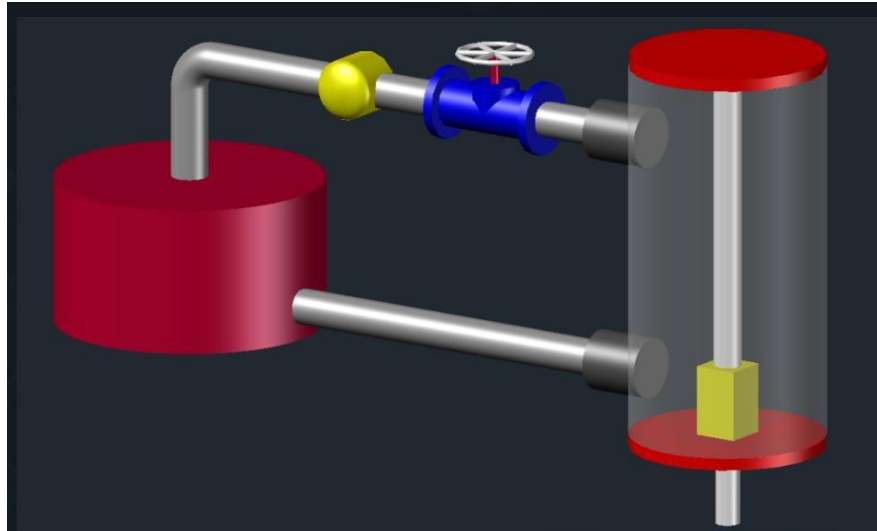


Figure 5. The experimental setup of alumina hollow fiber membrane module.

The second objective was to see how the number of alumina hollow fiber membranes inside the module used would relate to efficiency in separating oil and water. The results established that there exists a direct positive relationship between the number of hollow fiber membranes and the amount of oil collected. From *Table 2* and *Figure 6*, with one membrane, 10 ml of oil is separated; when two membranes are used, it increases to 30 ml; and with three membranes, 50 ml of oil is collected. It shows that adding more membranes significantly increases the surface area for oil-water separation, hence a better separation efficiency. The effective surface area offered by extra hollow fibers makes sure that more oil is collected from the emulsion, thus validating the assumption that greater number of membranes would result in better performance of oil/water separation.

Table 2. The amount of oil collected based on the different number of membranes.

| Number of alumina hollow fiber membrane | Amount of oil collected (ml) |
|---|------------------------------|
| 1 | 10 |
| 2 | 30 |
| 3 | 50 |

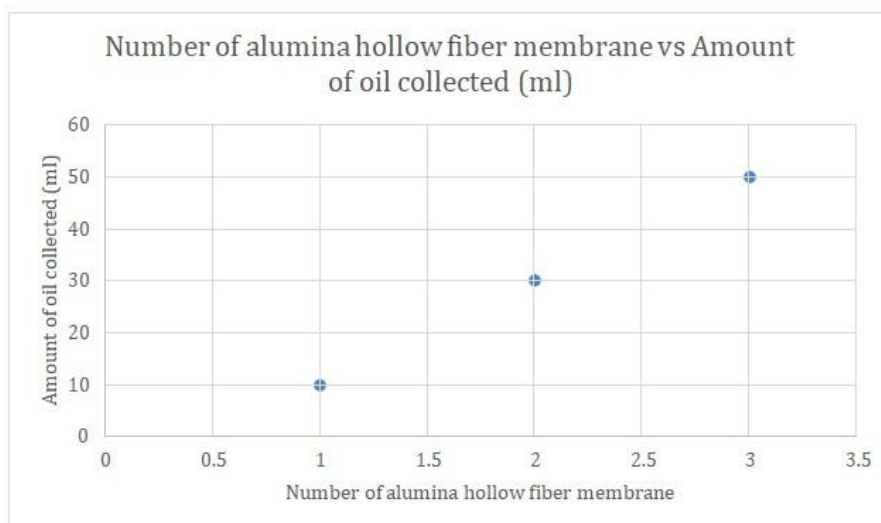


Figure 6. The number of membranes vs the amount of oil collected.

The ultimate goal observed the impact of different operating conditions on oil-water separation. Three major variables were changed: the concentration of oil, feed solution flow rate, and number of membranes inside the module. From *Table 3* and *Figure 7*, it is evident that more oil was collected with increasing concentration of oil in emulsion up to a certain point. At 30%, 50%, and 70% oil concentrations, the amounts of oil collected were 7 ml, 20 ml, and 13 ml respectively. At the highest concentration of oil, the efficiency of collection dropped because of fouling on the membrane. When oil sits on top of the membrane and its pores become blocked, then it will not work as well as it could. This shows results found by Baig et al. (2022) in 2022 who noted that fouling lowers by a great amount the efficiency of any type of separation system that works with membranes for wastewater treatment. The influence of flow rate on the separation of oils was equally studied. As seen in *Tables 4.3* and *Figure 4.6*, as the flow rate of the feed solution increased, more oil is collected. At $1.67 \times 10^{-5} \text{ m}^3/\text{s}$ there is a collection of 10 ml oil; at $2.0 \times 10^{-5} \text{ m}^3/\text{s}$ there is a collection of 13 ml; and at $2.3 \times 10^{-5} \text{ m}^3/\text{s}$ there is a collection of 19 ml oil, respectively. This has verified that higher flow rates allow more and better separation efficiency to be achieved since more oil will probably pass through the membrane, but also higher flow rates promote fouling especially at high concentration of oil, hence this can limit the membrane performance. The results of this study are aligned with existing literature on the field of membrane technology for industrial wastewater when repeating oil-water separation through alumina hollow fiber membrane modules. They do pose some new insights but, in general, seem to restate under-emphasized challenges, particularly from the perspective of fouling and operational parameters.

Table 3. The amount of oil collected based on the different concentration of the oil in oil-water emulsion.

| Concentration of oil in oil-water emulsion (%) | Amount of oil collected (ml) |
|--|------------------------------|
| 30 | 7 |
| 50 | 20 |
| 70 | 13 |

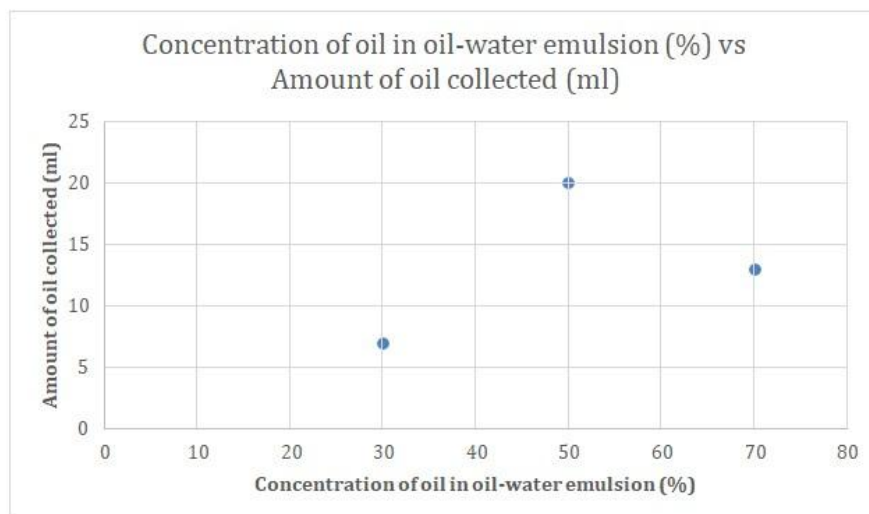


Figure 7. The concentration of oil in oil-water emulsion vs the amount of oil collected.

Impact of membrane surface area on separation efficiency

One of the main findings emerging out of this study is that increasing the number of alumina hollow fiber membranes increases the efficiency of oil collection, as tabulated in *Table 2* and illustrated graphically in *Figure 6*. This agrees with Wei et al. (2024), who had earlier emphasized that a larger membrane surface area provides more room or possibility for oil molecules to interact with hydrophobic membrane surfaces; thus, oil separation can be enhanced. Their study revealed that when more fibers are incorporated into any membrane module, total surface area increases contact points become available with oily wastewater to numerically possible contact points. This phenomenon was clearly corroborated by results obtained in this study where oil collected increased from 10ml with a singular membrane to 50ml using three membranes. Mousa et al. (2022) noted that increasing the membrane surface area enhances separation efficiency, particularly when wastewater treatments are applied as emulsions-without going into detail about the particular setup in which surface area makes it possible for more efficient trapping of oil. Just as well, they raise an issue-on increasing efficiency may also increase the tendency of the system to foul; hence a trade-off has to be considered. This substantively explains what has just been outlined above regarding fouling setting a limit on collection efficiency at higher concentrations of oil (70%) in this particular setup. More hollow fibers help in increasing separation (Baig et al., 2022). The performance may be marginal after a certain point, however, this proves that optimization is crucial in oil-water separation systems by reinforcing membrane numbers.

Effect of oil concentration and fouling

Another important result from this study is the effect that oil concentration has on separation efficiency. As can be seen in *Table 2* and *Figure 7*, the amount of oil collected increases with an increase in oil concentration in emulsion up to a certain point (50%) after which further increase in concentration (i.e. 70%) results to low collection of oil due to fouling. This can best be described through the results obtained by Wei et al. (2024), since they indicated that membrane fouling has a great effect on the separation efficiency at high oil concentrations within the feed solution. Fouling takes place when the surface of the membrane gets blocked by either oil molecules or emulsified droplets sitting on its surface pores and reduces the effective filtration area that can be utilized. The above observation also stands validated by a study carried out by Shirazi and Kargari (2015) regarding rapid fouling reducing efficiency at higher concentrations of oil during membrane distillation processes particularly if it is dealing with emulsified oil. Baig et al. (2022) thus further extended this by noting fouling in two ways: physical fouling, where oil physically blocks the pores of the membrane, and chemical fouling, where the oil interacts with and changes the properties of the membrane material. The present study reveals that hydrophobic an alumina membrane successfully permits permeation of oil, but when there is a buildup at high concentration, there is a drastic fall in efficiency in collecting the oil particularly at 70% concentration of oil. This speaks volumes about one of the major limitations for such breakthroughs in membrane-based separation technologies since challenges with fouling feed solutions containing high concentrations of oil exist. Another contribution to this fact is that of previous study who documented fouling as being quite problematic

toward treatment processes applicable to strong oily wastewater urging future studies on developing membranes resisting foul or implementing pretreatment steps to address this very problem.

Flow rate and its influence on separation performance

The third major operational parameter used in this study is the feed solution flow rate. A positive relationship between the flow rate and the amount of oil collected was seen, as tabulated in *Table 3* and illustrated graphically in *Figure 6*. The collected oil increased with an increase in the flow rate from 1.67×10^{-5} m³/s to 2.3×10^{-5} m³/s. This finding agrees with other previous findings like that of Shirazi and Kargari (2015) where it was found that the separation efficiency increases with an increasing flow rate because more oil can permeate through the membrane with a higher feed flow rate. Shirazi and Kargari (2015) brought another aspect to light where higher feed flows may increase separation but also introduce more fouling when there is more concentration of oil-in-water. Park et al. (2012) elaborated on the effects of varying flow rates in membrane-based separation systems and asserted that the relationship between flow rate and efficiency in separation is not straightforward. As per their study, higher flow rates increase pressure over the membrane which may result in enhanced permeation of the oil phase; however, if it surpasses the capacity of the membrane to separate oil from water then there is a possibility for fouling of the membrane and inefficiency. The current study also adjusted the flow rate to optimize the separation process but fouling was still an issue as high concentrations of oil were used. This proves that though increasing flow rate might enhance efficiency in separation, there has to be an optimum level which will keep fouling under control and hence ensure membrane sustainability.

Critical challenges in membrane technology for oil/water separation

This study on the effect of alumina hollow fiber membranes for oil-water separation discusses the challenges recently identified in the literature. The development of membrane modules for oil-water separation has been extensively studied, However, Mailler et al. (2023) found that the main problems facing membrane technology are fouling and high-pressure systems and also a short life span of the membrane when operating it under harsh conditions. As earlier discussed by Nasiri et al. (2017) ceramic membranes such as alumina membranes are known to possess mechanical strength and chemical stability against many weaknesses of fouling resistance, particularly when dealing with complex oily wastewater. Also, Molinos-Senante et al. (2012) noted that even though membrane tech has the plus of low energy use and no secondary waste, the cost to make the membrane and long-term costs for its replacement and upkeep are still big bars to large-scale industrial use. The results of this study back up these problems, mainly about fouling at high oil levels that could hurt the long-term work of the alumina hollow fiber membranes.

Conclusion

Findings of this study on the development of alumina hollow fiber membrane modules for oil/water separation accentuate and update existing perspectives into evolving waste management landscapes through treatment, especially among industries whose main challenge is over volumes with oily effluents. The study has evidenced that

increasing the number of membranes inside module increases efficiency in separation due to surface area directly provided by more fibers. This goes hand-in-hand with existing research in which the vital role surface area plays in improving performance during separation is highlighted (Wei et al., 2024; Mousa et al., 2022). However, this also brings about a complex interaction between surface area and other operating parameters, such as oil concentration, flow rate, and membrane configuration; on performance where fouling comes about mostly when membrane pores are blocked either by the molecules or emulsified droplets. This study observes further the fact that fouling becomes more intense at higher concentrations of oil, e.g., 70% corroborates other literature on the limitations of membrane systems when dealing with emulsions highly concentrated (Shirazi and Kargari, 2015). This brings to the fore one of several challenges that has continued to dog the application of membrane technology in wastewater treatment and among other industries where high concentrations of oil are being applied. It is another major discovery related to the balance between increasing flow rates through which one may enhance separation of oil and its encouragement for fouling that needs optimally balanced operational conditions for efficacy associated with long-term sustainability. The future evolution of membrane technology should regard research work concerned mainly with fouling management and also improvement in membrane endurance as well as system optimization for handling more oily content while maintaining efficiency.

From an industrial point of view, the successful application of alumina hollow fiber membranes in the process of oil-water separation would have great potential for waste water treatment solution enhancement where big volumes of oily effluents, as in gas and oil industries, are involved. Reduction in environmental impacts achievable by efficient emulsion oil-water separation would give these membranes a great possibility to present a sustainable option over traditional membrane separation methods, like centrifugation or chemical demulsification that involve even more operation costs and harmful effects towards the environment. However, there is still a long way before this technology is industrialized due to the very high cost of membrane materials and fouling management together with economic feasibility at a large scale. The use of alumina membranes adds mechanical strength and resistance against chemical degradation attacks but the price of ceramic membranes compared to polymeric alternatives is still a barrier to usage on a large adoption scale. Also, the issue of fouling has to be tackled so that the life and consistency of these membranes in practical applications can be improved. Hybrid membrane setups might emerge in the future with more pre-treatment or post-treatment methods added into inclusion adsorption or/and electrochemical processes to decrease fouling and increase efficiency. Material science developments such as using bioinspired coatings or nanomaterials may raise the efficiency of membranes and offer higher levels of fouling resistance. The integration of computational tools with operational parameters optimized by artificial intelligence could greatly assist in making operations more flexible, efficient, and sustainable. Therefore, this study is indubitably an advance that clearly racks a call for new designs in membrane innovation and discoveries regarding operating practices to unleash fully all possibilities that alumina hollow fiber membranes bear for oil-water separation under industrial circumstances.

Acknowledgement

This research is self-funded.

Conflict of interest

The authors confirm that there is no conflict of interest involve with any parties in this research study.

REFERENCES

- [1] Abuhasel, K., Kchaou, M., Alquraish, M., Munusamy, Y., Jeng, Y.T. (2021): Oily wastewater treatment: overview of conventional and modern methods, challenges, and future opportunities. – *Water* 13(7): 35p.
- [2] Ahmad, T., Guria, C., Mandal, A. (2020): A review of oily wastewater treatment using ultrafiltration membrane: A parametric study to enhance the membrane performance. – *Journal of Water Process Engineering* 36: 26p.
- [3] Adofo, Y.K., Nyankson, E., Agyei-Tuffour, B. (2022): Dispersants as an oil spill clean-up technique in the marine environment: A review. – *Heliyon* 8(8): 19p.
- [4] Baig, U., Gondal, M.A., Dastageer, M.A. (2022): Oil-water separation using surface engineered superhydrophobic and superoleophilic membrane for the production of clean water. – *Journal of Water Process Engineering* 45: 11p.
- [5] Baker, R.W. (2023): *Membrane technology and applications*. – John Wiley & Sons 560p.
- [6] Chen, J., Zhang, W., Wan, Z., Li, S., Huang, T., Fei, Y. (2019): Oil spills from global tankers: Status review and future governance. – *Journal of Cleaner Production* 227: 20-32.
- [7] Coca-Prados, J., Gutiérrez, G., Benito, J.M. (2012): Treatment of oily wastewater by membrane hybrid processes. – *Economic Sustainability and Environmental Protection in Mediterranean Countries through Clean Manufacturing Methods* 26p.
- [8] Gupta, R.K., Dunderdale, G.J., England, M.W., Hozumi, A. (2017): Oil/water separation techniques: a review of recent progresses and future directions. – *Journal of Materials Chemistry A* 5(31): 16025-16058.
- [9] Li, L., Xu, Z., Sun, W., Chen, J., Dai, C., Yan, B., Zeng, H. (2020): Bio-inspired membrane with adaptable wettability for smart oil/water separation. – *Journal of Membrane Science* 598: 9p.
- [10] Liu, J., Cui, Z., Hou, L., Li, D., Gao, Y., Shuai, L., Liu, J., Jin, J., Wang, N., Zhao, Y. (2019): Bioinspired membranes for multi-phase liquid and molecule separation. – *Science China Chemistry* 62(1): 14-23.
- [11] Liu, K., Tian, Y., Jiang, L. (2013): Bio-inspired superoleophobic and smart materials: design, fabrication, and application. – *Progress in Materials Science* 58(4): 503-564.
- [12] Mailler, R., Pouillaude, J., Fayolle, Y., Oliveira Filho, M., Causserand, C., Rocher, V. (2023): Long-term performances and membrane lifespan of full-scale MBR treating filtrate from sludge ultra-dewatering. – *Environmental Technology* 44(11): 1653-1666.
- [13] Molinos-Senante, M., Hernandez-Sancho, F., Sala-Garrido, R. (2012): Economic feasibility study for new technological alternatives in wastewater treatment processes: A review. – *Water Science and Technology* 65(5): 898-906.
- [14] Mousa, H.M., Fahmy, H.S., Ali, G.A., Abdelhamid, H.N., Ateia, M. (2022): Membranes for oil/water separation: a review. – *Advanced Materials Interfaces* 9(27): 60p.
- [15] Nasiri, M., Jafari, I., Parniankhoy, B. (2017): Oil and gas produced water management: a review of treatment technologies, challenges, and opportunities. – *Chemical Engineering Communications* 204(8): 990-1005.
- [16] Nour, H., Yunus, R.M., Jemaat, Z. (2007): Chemical demulsification of water-in-crude oil emulsions. – *Journal of Applied Sciences* 7(2): 196-201.
- [17] Park, N.S., Kim, S.S., Chae, S.H., Kim, S. (2012): The effect of fluctuation in flow rate on the performance of conventional and membrane water treatment for a smart water grid. – *Desalination and Water Treatment* 47(1-3): 17-23.

- [18] Shirazi, A.M.M., Kargari, A. (2015): A review on applications of membrane distillation (MD) process for wastewater treatment. – *Journal of Membrane Science and Research* 1(3): 101-112.
- [19] Wei, T., Chen, X., Guo, Z. (2024): Ceramic membrane composites for highly efficient oil–water separation: a review. – *Journal of Materials Chemistry A* 12(32): 20803-20837.
- [20] Xiang, B., Sun, Q., Zhong, Q., Mu, P., Li, J. (2022): Current research situation and future prospect of superwetting smart oil/water separation materials. – *Journal of Materials Chemistry A* 10(38): 20190-20217.