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# Evaluation of hydrophilic-coated ceramic membranes for cost-effective treatment of dye-contaminated wastewater

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**Keywords:** dye effluent, membrane, hardness, COD, CTAB.

**Abstract:** Rapid urbanization and the Industrial Revolution have resulted in large quantity of wastewater generation. Therefore, there is a need to explore sustainable options to treat and reuse it. This study investigates the removal of Texas dye, an industrial waste, from an aqueous solution using a cost-effective ceramic membrane. The ceramic membrane is manufactured using a mixture of 63 wt% bentonite, 3 wt% cetyltrimethylammonium bromide (CTAB), 2 wt% calcium carbonate, and 32 wt% quartz, and is fabricated using the hydraulic pressing method followed by sintering. The structural and morphological properties of the manufactured membrane are characterized using Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD). Experiments are conducted using a synthetic dye solution with an initial concentration of 100 mg/L, under a constant operating pressure of 1 psi and a hydraulic retention time of 60 minutes.
A novel hydrophilic surface modification is applied using Moringa oleifera leaf extract and silver nitrate solution. The modified membrane exhibits an improved permeability of 54.4% and an average pore size of 50 nm. The ceramic membrane shows promising removal efficiency of Texas dye. Reusability tests of the manufactured membrane demonstrate stable membrane performance over five continuous filtration cycles. The membranes are cleaned by backwashing, and removal tests are conducted for further nine cycles. The membrane maintains high removal efficiency of Texas dye, as measured in chemical oxygen demand (COD), as well as hardness, during the first five cycles. This research highlights the potential of ceramic membranes for efficient, low-pressure dye removal and wastewater treatment, with enhanced durability and reusability.

## Introduction

The global water crisis is a growing global issue, and wastewater treatment has emerged a critical strategy to address the scarcity of clean water. Wastewater, particularly from industrial activities, often contains harmful chemicals, heavy metals, and other pollutants that pose significant risks to the environment and public health. Addressing these challenges requires extensive research to develop new and cost-effective water purification techniques (Do Carmo., 2024). Conventional methods such as adsorption, filtration, and biological treatment have long been used in wastewater treatment and remain integral to many systems due to their effectiveness and adaptability (Ugarte P., 2022). In recent years, membrane filtration has advanced significantly, making it one of the most effective and widely adopted technologies for both water and wastewater treatment (Nandi., 2011). Its advantages include high removal efficiency, low chemical consumption, and the ability to produce high-quality water. The method is a very efficient way to treat water and wastewater in both urban and industrial settings because of these advantages as well as its small size, scalability, and dependability (Lorente-Ayza., 2017) (Qi, 2025).

Despite these advantages, membrane filtration systems face economic challenges. However, ongoing research focused on developing durable membrane materials, improving energy efficiency, and optimizing cost-effective pre-treatment methods is making this technology increasingly accessible and sustainable (Issaoui., 2019) (Baig., 2024). Membranes used in water treatment are broadly classified into polymeric and ceramic types (Rackcho et.al., 2023). Both polymeric membranes and ceramic membranes face challenges related to fouling, maintenance, cost, and performance (Suresh et.al., 2016) (Fooladi et.al., 2024) (Fu, 2024). Despite being flexible and reasonably priced, polymeric membranes are prone to fouling, chemical degradation, and have a limited operational lifespan (Latwal M, 2023). In contrast, ceramic membranes exhibit superior chemical and thermal stability but suffer from drawbacks, including fragility, higher initial costs, and more intensive cleaning requirements (Dos Santos Barbosa et.al., 2024).

In order to overcome these limitations, current research focused on enhancing membrane durability, reducing costs, and improving cleaning efficiency. Additionally, hybrid systems that combine the advantages of both polymeric and ceramic membranes are being explored (Akash F.A et.al., 2024). In this context, our study focuses on ceramic membranes as a promising approach for treating dye-contaminated wastewater and eliminating hazardous pollutants. Although ceramic membranes are generally more expensive than polymer membranes, they often demonstrate superior removal efficiency (Akash F.A et.al., 2024)(Sawunyama L . et.al., 2024). To lower the initial cost, various studies have explored the use of organic materials and waste-derived materials in ceramic membranes (Kumar R.V., 2016). Common materials include chokebore clay, kaolin, bentonite, quartz (Rahma A., 2023), (Alijil S., 2020).

In our study, we fabricated a membrane using bentonite clay, which is renowned for its high plasticity and refractory properties. Additionally, CTAB (cetrimonium bromide), quartz, and $CaCO_3$ were used to enhance the properties of ceramic membrane. A hydrophilic coating was applied to improve the performance of membranes in filtration processes. The use of a combination of *Moringa oleifera* and silver nitrate for hydrophilic coating significantly improves membrane performance, reduces fouling, and enhances membrane longevity.

## Experimental study

### Materials

Raw materials used to fabricate the ceramic membrane in this study are bentonite clay, CTAB, $CaCo_3$ & quartz. Bentonite ($Al_2H_2O_6Si$) is renowned for its high plasticity and refractory properties, whereas C-tab ($C_{19}H_{42}BrN$) is known for its binding properties. Additionally, the addition of $CaCo_3$ promotes pore formation, while quartz ($SiO_2$) serves as a filtration medium with exceptional mechanical strength and thermal stability.

### Preparation of Membrane

A membrane with a diameter of 10 cm and a thickness of 1 cm was prepared using a mixture of (wt%) 63% Bentonite, 3 wt% CTAB, 2% wt calcium carbonate, and 32 wt% quartz in the dry state. Water was added continuously until the required plastic limit was achieved to reduce brittleness. The membrane was fabricated using a mould and dried at room temperature for 3 days. To prevent cracking during drying, a controlled thermal treatment was applied. Initially, the membrane was oven-dried at temperatures ranging from 25 °C to 150 °C for 3 hours to reduce moisture content. This was followed by heating in a muffle furnace from 150 °C to 300 °C for 1 hour. Subsequently, the membrane was gradually sintered by increasing the temperature from 300 °C to 600 °C for 1 hour, and then from 600 °C to 800 °C for additional 1.5 hours. Finally, the membrane was allowed to cool to room temperature. The membrane before hydrophilic coating is shown in Figure 1.

### Hydrophilic coating

In order to enhance membrane performance and mitigate fouling and bacterial contamination, a hydrophilic coating based on *Moringa olifera* leaves and silver nitrate solution was applied using a dip-coating method (Moharrami M et.al., 2025), (Malik N, 2020). *Moringa olifera* contains cationic proteins that facilitate coagulation and clarification of turbid water by attracting suspended particles and bacteria. In contrast, $AgNO_3$ inhibits the growth of bacteria and other microorganisms on the membrane surface, thereby reducing fouling. *Moringa oleifera* leaves were collected, dried, and ground into a fine powder (Bialowas M., 2024), (Boonphan S., 2024). This powder was then mixed with distilled water, boiled for an hour, and filtered to obtain the *Moringa* extract solution. Subsequently, 2.5 ml of the extract solution was mixed with 10ml of silver nitrate solution. The appearance of a reddish-brown color indicated the presence of silver nanoparticles. The preparation process of the hydrophilic coating on the ceramic membrane is shown in Figure 2.

### Characterization of membrane

Figure 3 shows the surface morphology of bentonite, $CaCo_3$, CTAB, and quartz used in the fabrication of the membrane, imaged at approximately 2 kx magnification, an accelerating voltage of 3kv, and working distance of 13 mm. The images reveal that the nanoparticles exhibit a spherical shape with an average diameter of 50nm.

Figure 3 (a) shows that bentonite clay consists of small, slender, plate-like particles, typically arranged in stacked and iirregularly formedlayers or clusters. Figure 3(b) illustrates the aggregation of $CaCo_3$ particles, which contributes to pore formation within the ceramic membrane. Figure 3(c) and 3(d)

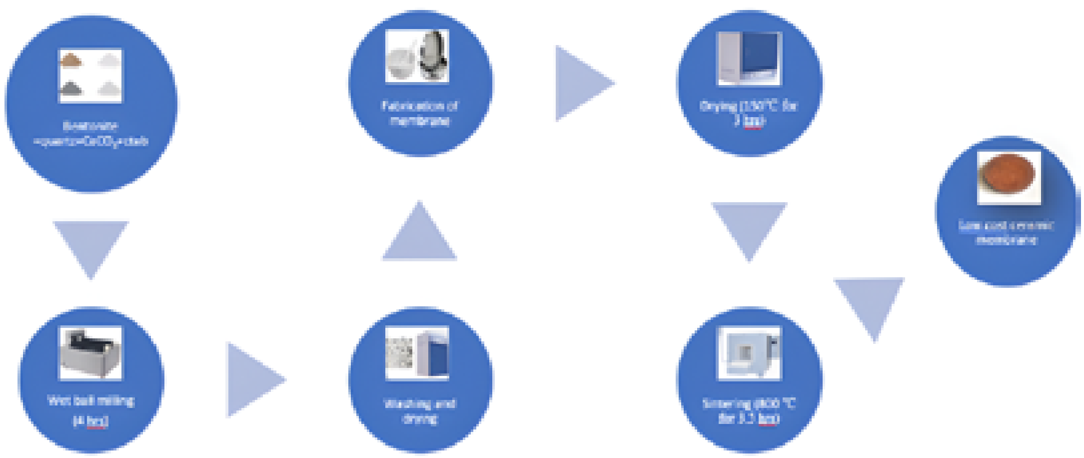



**Fig. 1.** Flow Diagram of fabrication of low cost ceramic membrane


**Fig. 2.** Process of hydrophilic coating of the membrane

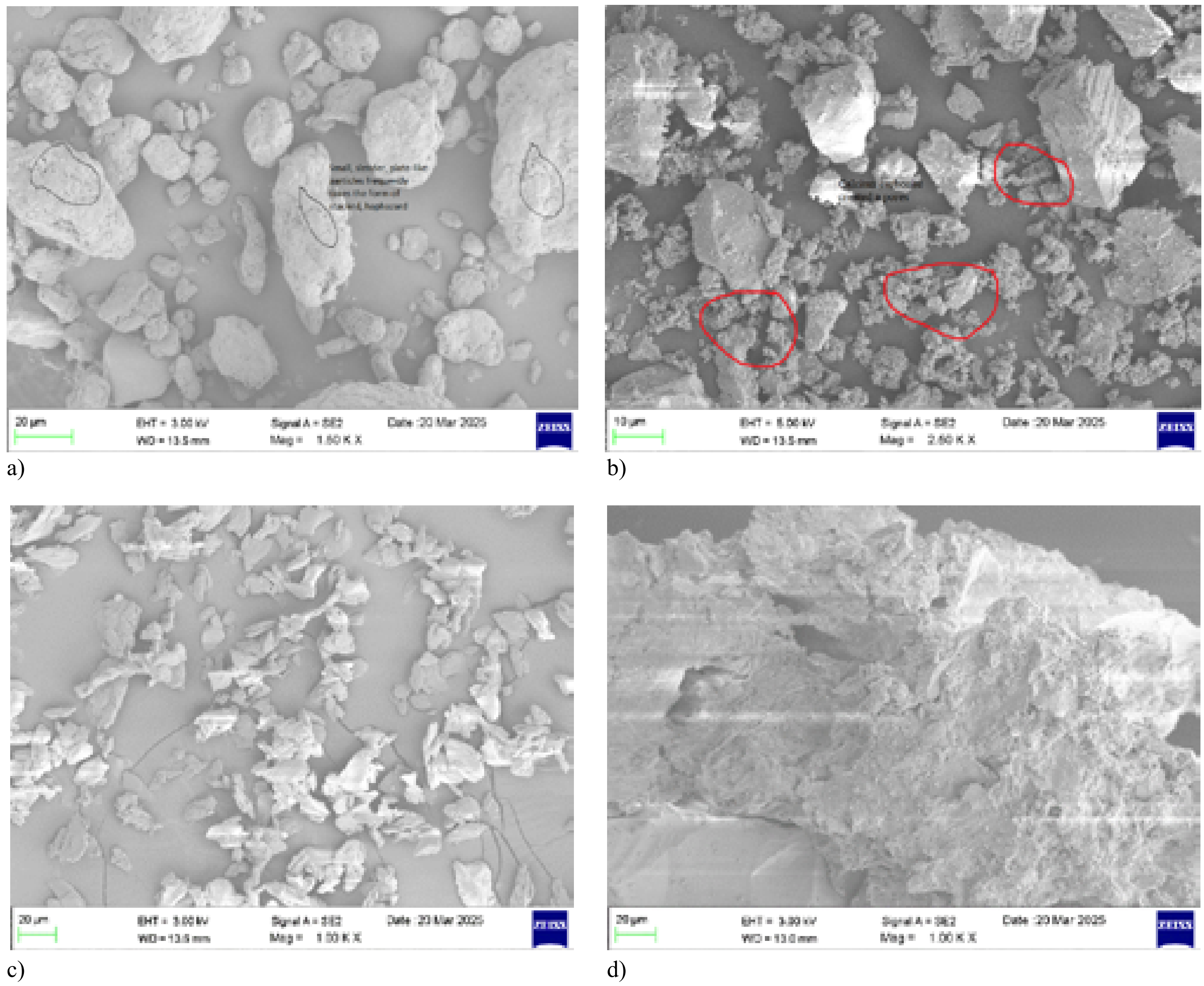



**Fig. 3.** SEM image of a) Bentonite, b) CaCO3, c) C- Tab, d) Quartz

indicate that CTAB and quartz act as effective binding agents between the ceramic constituents.

***Permeability:***

The apparent porosity was determined using the immersion method based on Archimedes' principle, with water as the immersion fluid, in accordance with ASTM C 20 (2000) (Do Carmo, 2024).

$$P = \frac{Wet\ weight(Ww) - Dry\ weight(Dw)}{Wet\ weight - Immersed\ weight(Iw)} \cdot 100 \quad (1)$$

The porosity of the ceramic membrane was calculated using the above formula, with water as the immersion fluid, and expressed as a percentage. After the application of hydrophilic coating, the membrane porosity was also determined (Khalil A, 2024). These findings indicate that the membrane's permeability can be enhanced through coating. Coating of membranes is an effective strategy to improve performance by increasing water permeability, reducing fouling, and extending membrane lifespan (Fooladi et.al., 2024).

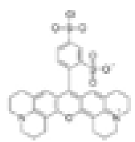
### *Reusability of the ceramic membrane*

To evaluate the reusability of the low-cost ceramic membrane, repeated filtration cycles were performed. Five cycles were conducted without backwashing. Chemical cleaning is necessary to ensure complete removal of feed solution deposits (Alkhouzaam A., 2024), (Abdullayev A, 2019). After the fifth cycle, the membrane became clogged with impurities; therefore, backwashing was performed using clean water, followed by soaking the membrane in $H_2SO_4$for 20 minutes. After acid cleaning, the membrane was reused for additional 4 cycles, based on the effluent water characteristics.

### *Dye water*

The synthetic dye wastewater sample water was prepared by dissolving 0.05g Texas Red dye in 1 liter of distilled water. The dye concentration was 0.05g/L, and the initial pH was 6.1. Texas Red is a sulfonated azo dye, chemically known as 2-(4-(dimethyl amino) phenyl)-1H-benzimidazole-1, 3(2H)-dione. It typically has an excitation maximum around 595 nm and an emission maximum around 615 nm. The dye characteristics provided by the manufacturer are summarized in Table 1.

**Table 1:** Texas Red Dye characteristics

| | |
|---|---|
| Molecular formula | $C_{31}H_{30}N_2O_6S_2$ |
| Chemical structure |  |
| Molecular mass (g/mol) | 864.30 |
| Charge | anionic dye |
| Wavelength ($\lambda_{max}$)(nm) | 595 |
| Molar volume ($cm^3$/mol) | 1380 g/mol |

## Results and Discussion

### *Chemical composition of ceramic powder*

The chemical composition of materials was determined by X-ray diffraction (XRD) analysis and is presented in Table 2. The results indicate that CTAB contains tungsten oxide ($WO_3$) nanoparticles, which are promising for water treatment applications due to their photocatalytic properties, enabling the degradation of pollutants under visible light, and their ability to adsorb pollutants.

Bismuth trioxide ($Bi_2O_3$) nanoparticles are being explored for water treatment applications due to their photocatalytic and antibacterial properties, enabling the degradation of pollutants and suppression of microbial growth. According to Table 2, $Bi_2O_3$ is detected in CTAB and $CaCo_3$-containing samples. Calcite, a naturally occurring form of calcium carbonate ($CaCO_3$), is widely used in water treatment to neutralize acidic water, increase pH, and reduce corrosivity. It is also used to re-mineralize water after reverse osmosis and can contribute to the reduction of heavy metal contamination. Oxo niobium phosphate ($NbOPO_4$) can be used in water treatment, particularly for phosphate removal and as a solid acid catalyst. Niobium oxide ($Nb_2O_5$) and niobium phosphate (NbPO) are materials that have shown promising results in removing phosphate ions from water. Additionally, niobium-based materials like mesoporous niobium oxophosphate (NBP) are being explored for their catalytic activity in aqueous reactions.

From Figure 4 (a), the XRD pattern confirms the presence of silica and aluminum phosphate ($Al_2P$) in the bentonite clay matrix. These constituents enhance the material's adsorption capabilities, enabling effective removal of organic pollutants such as dyes from wastewater through surface interactions and ion exchange mechanisms. Figure 4 (b) shows the XRD pattern of the CTAB-modified sample. The dominant peaks correspond to tungsten oxide ($WO_3$) and bismuth molybdate ($Bi_2MoO_6$), indicating the formation of crystalline photocatalytic phases. The presence of $WO_3$ is crucial for the degradation of organic pollutants in dye-contaminated water due to its visible-light photocatalytic activity. Figure 4 (c) presents the XRD pattern of the quartz-modified sample. The broad peak centered around ~28° 2θ corresponds to niobium phosphate ($NbO_4PO_4$), suggesting the presence of an amorphous or poorly crystalline niobium-based phase. The broad hump in the diffraction pattern indicates a partially amorphous structure, which is often associated with higher surface area and enhanced adsorption capacity. Figure 4 (d) shows a pattern corresponding to calcite, one of the most thermodynamically stable forms of calcium carbonate.

**Table 2:** Chemical composition of ceramic powder

| Chemical composition | $SiO_2$ (%) | $Al_2P$ (%) | $Bi_2O_3$ (%) | $WO_3$ (%) | $NbOPO_4$ |
|---|---|---|---|---|---|
| Bentonite clay | 30 | 63.0 | | | |
| CTAB | | | 15 | 35 | |
| $CaCO_3$ | | | 11 | | |
| Quartz | | | | | 42 |

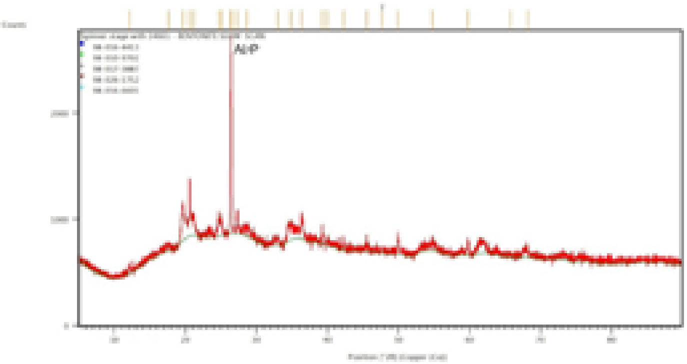


**Fig. 4a.** Chemical composition of bentonite clay

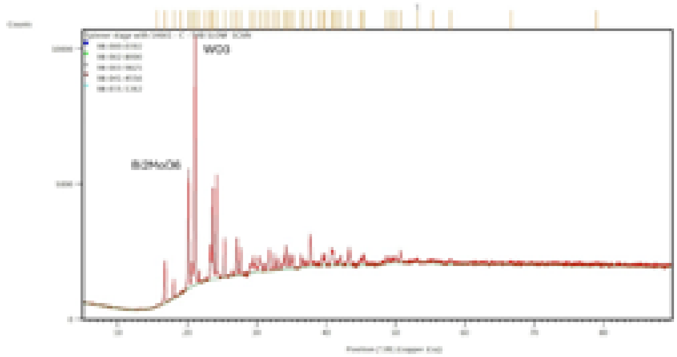


**Fig. 4b.** Chemical composition of C-TAB

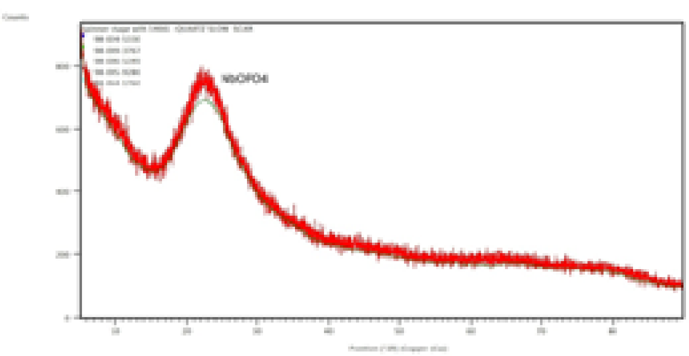


**Fig. 4c.** Chemical composition of Quartz

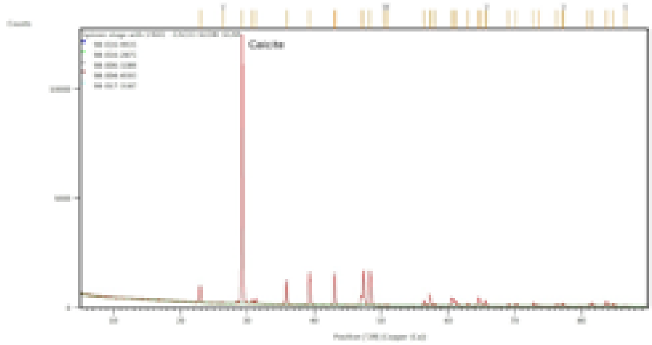


**Fig. 4d.** Chemical composition of $CaCO_3$

### *Experimental setup*

The experimental setup consists of an influent tank from which the water to be treated is pumped to the ceramic membrane, as shown in Figure 5.

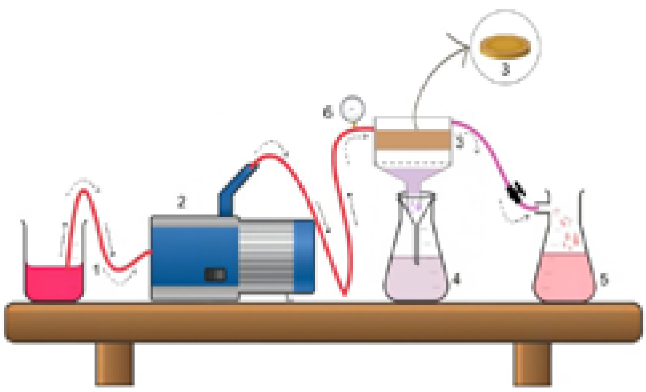


**Fig. 5.** Laboratory scale membrane filtration setup. 1. Influent tank 2. Pump 3.Ceramic

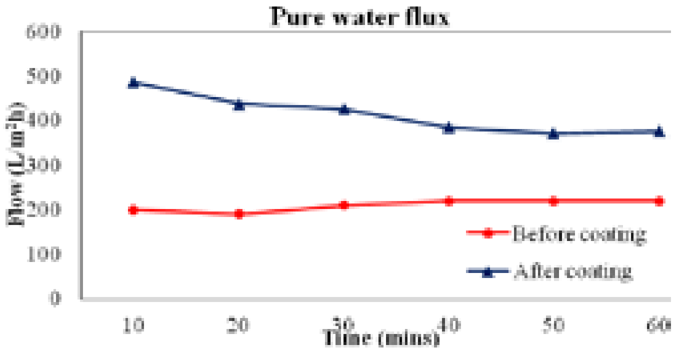



**Fig. 6.** Pure water flux for permeability study

### *Permeability of ceramic membrane*

Permeability is an important parameter for evaluating ceramic membrane. performance Therefore, the permeability of the membrane was analyzed by comparing the flow of pure water and dye solution through the ceramic membrane (Silveira C., 2025).

The above graph illustrates the variation in pure water flux over time for ceramic membranes before and after coating. The uncoated membrane exhibited a relatively low and stable flux, fluctuating slightly around 200–225 L/m²·h over 60-minute duration, indicating limited permeability. In contrast, the coated membrane showed a significantly higher initial flux of approximately 480 L/m²·h at 10 minutes, which gradually decreased to around 370 L/m²·h at 60 minutes. Despite this decline, the coated membrane consistently maintained a higher flux than the uncoated membrane, demonstrating the effectiveness of the coating process in improving membrane hydrophilicity and pore structure. The gradual decrease in flux may be attributed to minor pore compaction or the progressive development of fouling resistance over time. Nevertheless, the results show that surface modification through coating significantly enhances the water permeability of the ceramic membrane, thereby improving its suitability for high-throughput filtration applications.

Figure 7 illustrates the dye water flow across ceramic membranes over time and compares performance before and after surface coating. The uncoated membrane showed

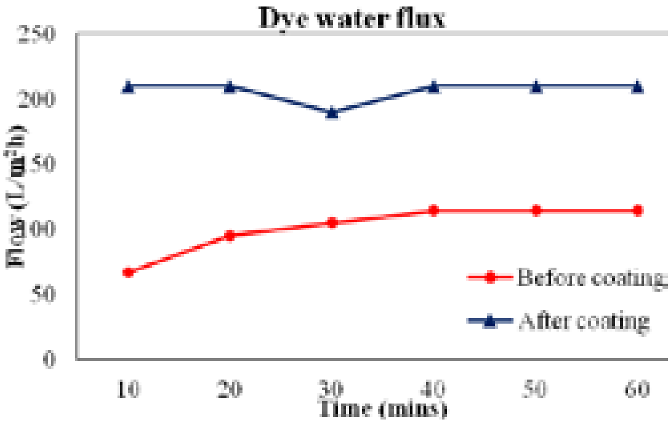



**Fig. 7.** Dye water flux for permeability study

a gradual flux increase, rising from approximately 68 L/m²h at 10 minutes to a peak of about 115 L/m²h at 40 minutes, indicating limited and time-dependent dye permeability. In contrast, the coated membrane showed significantly higher and more stable flux values, maintaining approximately 210 L/m²h throughout the 60-minute period, with only a slight decrease observed around the 30-minute mark. This stability and improved performance following coating show that the membrane surface modification effectively enhances dye solution permeability and antifouling properties. According to the observed results, the coating procedure greatly improves membrane efficiency in treating dye-containing wastewater, making it a promising strategy for sustainable water treatment applications.

The performance improvement of the ceramic membrane after coating is evident from the comparison of pure water flux and dye solution flux under both clean and dye-contaminated conditions. In pure water flux test, the coated membrane displayed significantly higher flux values, initially around 480 L/m²·h and gradually decreasing to ~370 L/m²·h over time, likely due to minor fouling or resistance buildup. In contrast, the uncoated membrane displayed a relatively low and stable flow rate ranging from ~190 to 220 L/m²·h in the pure water flux graph. A more pronounced difference is observed in the dye solution flux results. Over 60 minutes, the uncoated membrane flux increased gradually from about 68 L/m²·h to approximately 115 L/m²·h, most likely as a result of slow dye particle deposition that blocked pores. However, the coated membrane showed improved dye rejection and a decreased fouling tendency, maintaining a constant higher flow (~210 L/m²·h) with only minor fluctuations.

These results collectively demonstrate that membrane coating greatly enhances operational stability and fouling resistance under challenging, real-world circumstances, such as dye-laden wastewater, while also improving baseline permeability as observed in pure water flux. This highlights the coating's ability to maintain high permeability and operational reliability, which makes it suitable for sustainable industrial wastewater treatment applications.

**Table 3:** Experimental study for ceramic membrane for fouling performance

| Cycle No | Cleaning Set up | Flow rate (l/hr) | | Trans membrane Pressure (Bar) | Permeate Volume (L) | | Observation |
|---|---|---|---|---|---|---|---|
| | | Before Coating | After Coating | | Before Coating | After Coating | |
| 1 | None | 1.2 | 1.5 | 1 | 0.72 | 1.32 | Normal operation |
| 2 | None | 1.2 | 1.5 | 1 | 0.72 | 1.32 | Slight decline in flow rate |
| 3 | None | 1.1 | 1.5 | 1 | 0.6 | 1.2 | Progressive fouling |
| 4 | None | 1 | 1.5 | 1 | 0.42 | 1.02 | Increased fouling signs |
| 5 | None | 1 | 1.2 | 1 | 0.24 | 0.72 | Significant fouling, cleaning required |
| 6 | Physical + Acid Cleaning ($H_2SO_4$) | 1.1 | 1.5 | 1 | 0.66 | 1.14 | Flow restored after cleaning |
| 7 | None | 1.1 | 1.5 | 1 | 0.66 | 1.14 | Stable performance |
| 8 | None | 1 | 1.4 | 1 | 0.54 | 0.96 | Slight decline |
| 9 | None | 1 | 1.2 | 1 | 0.54 | 0.9 | Noticeable fouling |
| 10 | None | 0.9 | 1.2 | 1 | 0.36 | 0.6 | Noticeable fouling |
| 11 | None | 0.7 | 1 | 1 | 0.22 | 0.66 | Noticeable fouling |
| 12 | None | 0.7 | 1 | 1 | 0.11 | 0.48 | Fouling occurred continuously |
| 13 | None | 0.5 | 1 | 1 | 0.11 | 0.45 | Fouling occurred continuously |
| 14 | None | 0.5 | 0.8 | 1 | 0.11 | 0.42 | Fouling occurred continuously |
| 15 | None | 0.5 | 0.8 | 1 | 0.11 | 0.42 | Fouling occurred continuously |

### *Study of membrane performance*

The data in Table 3 indicate that the hydrophilic-coated ceramic membrane consistently outperformed the uncoated membrane over 15 filtration cycles. Specifically, the coated membrane maintained higher flow rates and permeated volumes under similar transmembrane pressures, even as fouling progressed. Although both membranes experienced fouling over time, the coated membrane exhibited greater fouling resistance, as evidenced by a slower decline in flow rate and permeating volume. Following physical and acid cleaning at cycle 6, the coated membrane showed a higher performance recovery compared to the uncoated membrane, suggesting improved cleanability and durability. Despite gradual fouling accumulation in subsequent cycles, the coated membrane sustained relatively stable operation for a longer duration than the uncoated membrane.

These observations suggest that the hydrophilic surface modification enhances membrane performance by mitigating fouling and facilitating effective cleaning, thereby extending membrane lifespan and improving treatment efficiency for dye-contaminated wastewater.

From figure 8, it is evident that the hydrophilic-coated ceramic membrane maintains a substantially higher flow rate compared to the uncoated membrane throughout the 15 filtration cycles. Initially, the coated membrane exhibits a flow rate of approximately 1.5 L/h, while the uncoated membrane begins at around 1.2 L/h, as shown in cycle 1 (Table 4). This difference persists and becomes more pronounced over subsequent cycles. Over time, both membranes show declining flow rates due to fouling; however, the coated membrane shows a much more gradual decrease. For example, at cycle 10, the coated membrane maintains a flow rate of approximately 1.2 L/h, whereas the uncoated membrane drops to approximately 0.9 L/h. The slower decline and higher sustained flow of the coated membrane are consistent with the trends observed in Table 4, where permeate volume and flow rate remain significantly higher even under fouling conditions and after cleaning. Notably, after cleaning at cycle 6, the coated membrane demonstrates a recovery in flow closer to initial value. Overall, the coated membrane exhibits improved fouling resistance and better performance recovery, as reflected by its consistently higher and more stable flow rate curve compared to the steep decline observed for the uncoated membrane.

From figure 9, it is evident that the hydrophilic-coated ceramic membrane maintains a substantially higher permeate volume compared to the uncoated membrane throughout the 15 filtration cycles. Initially, the coated membrane exhibits a permeate volume of approximately 1.32 L, while the uncoated membrane starts near 0.72 L, as shown in cycle 1 (Table 4). This difference persists and becomes more pronounced over subsequent cycles. Over time, both membranes experience a decline in permeate volume due to fouling; however, the coated membrane shows a much more gradual decrease. The slower decline and higher sustained permeate volume of the coated membrane are consistent with the trends in Table 4 , where permeate volumes and flow rates remain significantly higher even under fouling conditions and after cleaning.

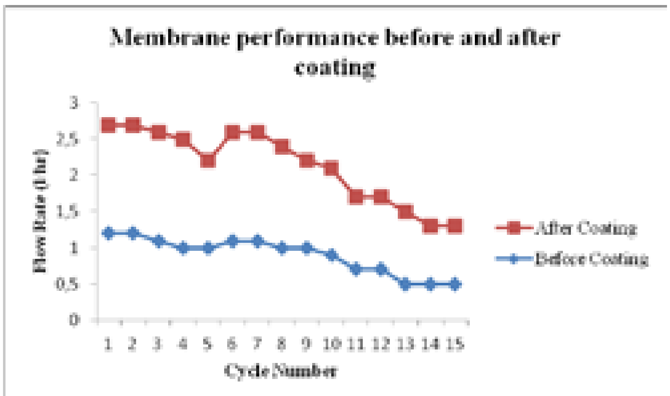



**Fig. 8.** Membrane Performance with respect to flow rate

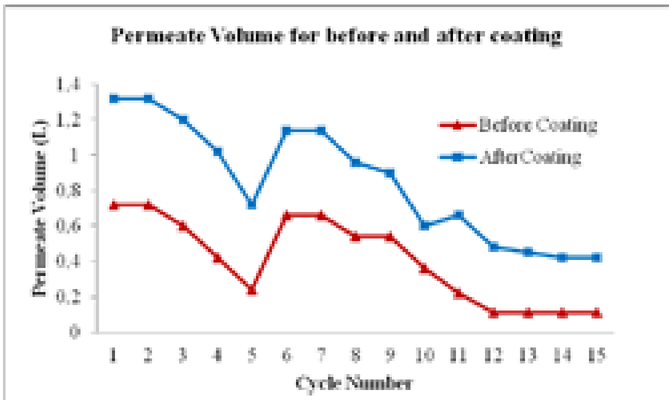



**Fig. 9.** Membrane Performance with respect to permeate volume

### *Variation of pH of the treated water*

Figure 10 shows the pH variation across fourteen experiments conducted during the fabrication and application of the low-cost ceramic membrane for dye water treatment. In the initial trials (I–V), there is minimal acid-base interaction, as indicated by relatively stable pH values ranging from 6.4 to 6.8. A noticeable gap before to trial VI, which was probably caused by either membrane conditioning or changes to the process. A steady downward trend is seen from trial VI onward, with pH readings progressively dropping from 6.6 is observed prior to trial VI, which may be attributed to membrane conditioning or operational adjustments. From trial VI onward, a gradual decreasing trend in pH is observed, with values declining from approximately 6.6 to 6.2 by trial XIV. This decrease may be associated with progressive adsorption and removal of dye molecules, the formation of minor acidic byproducts, or changes in membrane surface properties during repeated use. Overall, the results indicate that the pH of the treated water remains relatively stable, fluctuating within a narrow range of approximately 6.2 to 6.8, suggesting that the membrane treatment process does not significantly alter the neutrality of the effluent.

### *Removal efficiency of membrane*

Figure 11 illustrates the variation in treatment efficiency, providing a clear representation of the performance of the low-cost ceramic membrane in removing hardness and chemical oxygen demand (COD) from dye wastewater before and after backwashing. Prior to backwashing (trials I–V), both COD and hardness removal efficiencies are high, with COD removal ranging from 90 to 93% and hardness removal consistency

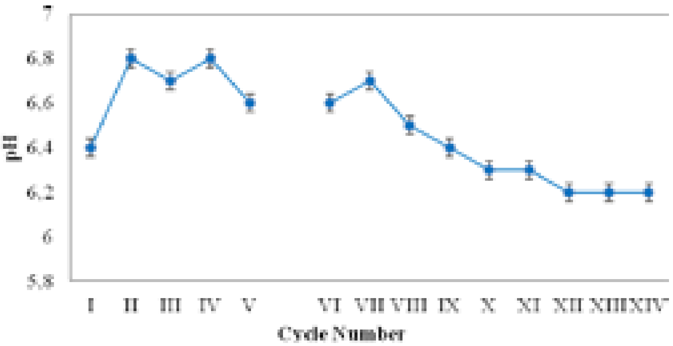



**Fig. 10.** Rejection coefficient of Dye water for pH

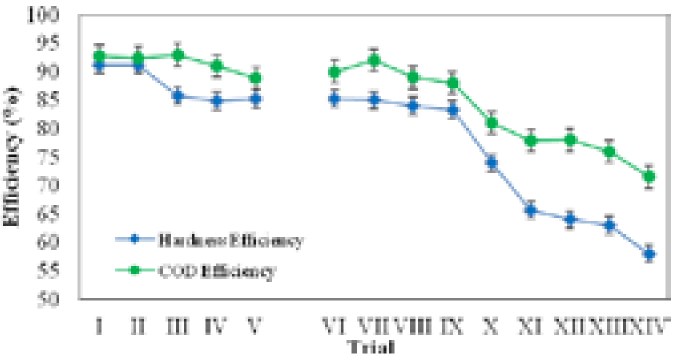



**Fig. 11.** Rejection coefficient of Dye water for Hardness and COD

above 85%. However, both parameters show a gradual decline following backwashing (trials VI–XIV). COD removal efficiency decreases from approximately 92% to 72% over the course of the experiment, suggesting progressive membrane fouling or a reduction in adsorption capacity. Similarly, hardness removal efficiency declines from about 84% to 58% by the final trial. These results suggest that while backwashing improves performance to some extent, it might not fully restore the membrane's initial functionality and porosity, particularly for hardness ions. These findings confirm the membrane's initial high efficacy but also highlight limitations in long-term reusability without more intensive regeneration or advanced cleaning strategies.

### *Cost analysis of ceramic membrane*

The detailed cost analysis of the fabrication of the membrane with a diameter of 10 cm and a thickness of 1 cm used in the study is shown in Table 4.

It is evident from Table 2 that the total cost of manufacturing a single ceramic membrane which requires 132.665 $cm^3$ of raw materials for the laboratory-scale production, is ₹148.59. This cost estimate can be used as a baseline for future research aimed at scaling up or optimizing material utilization while also providing insight into the economic feasibility of membrane fabrication at the laboratory scale. This cost of the ceramic membrane is comparatively lower than that of other reported ceramic membranes (Mouiya M, 2018) (Chikri R, 2024).

## Conclusion

In this study, the permeability, dye rejection, and reusability of a low-cost ceramic membrane were evaluated before and after surface coating. Due to increased hydrophilicity and reduced fouling tendency, the coated membrane demonstrated significantly improved pure water and dye solution fluxes, while maintaining higher and more stable permeability compared to the uncoated membrane. The coated membrane sustained a relatively constant dye solution flux of about 210 L/ $m^2$•h, whereas the uncoated membrane showed lower and less stable performance.

Based on rejection efficiency measurements, the membrane initially achieved effective removal of hardness and COD, with efficiencies exceeding 90% for hardness and over 85% for COD. However, after repeated backwashing cycles, a decline in performance was observed, particularly in hardness rejection, indicating gradual membrane deterioration or loss of

**Table 4:** Cost analysis for fabrication of ceramic membrane

| Cost Category | Item | Quantity Used | Unit Cost (INR) | Total Cost (INR) |
|---|---|---|---|---|
| **Raw Materials** | Bentonite clay | 63g | ₹440/kg | ₹27 |
| | Quartz | 32g | ₹600/kg | ₹19 |
| | $CaCo_3$ | 2g | ₹500/kg | ₹1 |
| | CTAB | 3g | ₹5600/kg | ₹17 |
| | $AgNo_3$ | 10mg | ₹9000/litre | 9 paisa |
| | **Subtotal** | | | **₹64** |
| **Processing** | **Sintering** | | | |
| **Equipment** | Oven | 3 hrs | ₹13/unit | **₹39** |
| | Muffle Furnace use | 3.5 hrs | ₹13/unit | ₹45.5 |
| **Total Cost** | | | | **₹148.5** |

active sites. Furthermore, pH monitoring revealed that repeated operation slightly influenced the treated water chemistry, with a marginal shift toward lower pH, while maintaining near-neutral conditions. To ascertain whether large-scale implementation for industrial wastewater treatment is feasible, it will also be crucial to scale up the membrane manufacture and testing procedures. To fully utilize coated ceramic membranes as an economical and environmentally friendly method of treating wastewater contaminated with dyes, several factors must be addressed. Although better regeneration techniques could be needed for long-term performance, the results generally show that surface coating greatly improves the performance and durability of ceramic membranes, making them attractive for the economical and sustainable treatment of dye-contaminated wastewater.

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