

Fouling-regeneration mechanisms and life time prediction of rice husk-derived low-cost ceramic membranes for pretreatment-assisted peat water treatment

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ABSTRACT

Peat water treatment is limited by high dissolved organic matter, acidity, colour, and membrane fouling. The fouling–regeneration behaviour and operational lifetime of a rice husk-derived low-cost ceramic membrane used after sequential pretreatment were investigated in this study. The tubular membrane was prepared from natural clay, rice husk activated carbon, and Fe₂O₃ at 82.5 : 15.0 : 2.5 wt.% and sintered at 900 °C. The membrane was characterised by SEM-EDS, elemental mapping, XRD, TGA, image analysis, and Archimedes method. Peat water was pretreated by sedimentation, slow-sand filtration, sponge filtration, and activated-carbon adsorption before membrane filtration at 2 bar. Six filtration–backwashing cycles were performed, and fouling was interpreted by using the classical Hermia models. The membrane showed a heterogeneous porous structure with an average porosity of 47.927% and a high thermal stability. Turbidity, colour, Fe, Mn, and nitrite were removed in 98.87%, 91.05%, 98.00%, 97.10% and 99.92%, respectively, and removal of detectable *E. coli* as well as *total coliform* was achieved by the integrated system. Fouling developed from internal pore constriction resulting in cake layer formation and more serious pore blocking. The backwashing hydraulic flow reached 95.60–94.23% of flux recovery ratios. However, the irreversible fouling increased from 4.40 to 5.77%, and the filtration time decreased from 77 to 13 h. Recovered flux followed $J_n/J_0 = e^{[-0.0498(n-1)]}$ with $R^2 = 0.9958$. Membrane lifetime was estimated to be 8.17 cycles or 211 h at 70% end-of-life threshold. The membrane thus provides high quality peat water polishing, but requires increased periodic cleaning to limit the accumulation of irreversible fouling.

Keywords: peat water, fouling regeneration, low cost ceramic membrane, backwashing, Hermia models.

INTRODUCTION

Peat water is one of the most complex natural raw waters to treat because of characteristics such as high concentrations of dissolved organic matter, dark-brownish colour, low pH, as well as dissolved humic and fulvic acids (Nasir et al., 2024). These properties reduce water quality and restrict the direct use of water, especially for domestic and community purposes in peatland areas (Ali

et al., 2021). Ordinary treatment processes, including coagulation, sedimentation, filtration, and adsorption, are often used to enhance peat water quality (Yulianto et al., 2024). However, their efficiencies may vary depending on the concentration and composition of organic compounds (Xie et al., 2025). Thus, building affordable, sustainable, and efficient treatment methods will still be the cornerstone of enabling the delivery of clean water in such peatland areas.

The compactness of the system, high separation efficiency, and foils (no porous cut membrane) to retain suspended solids, colloids, and organic matter make membrane filtration a widely researched technology for water and wastewater treatment (Hosseinzadeh et al., 2025). Membrane processes have been combined with specific pretreatment methods to enhance turbidity, colour, and organic matter removal in peat water treatment (Fitriana et al., 2025). However, membrane fouling is still a critical barrier limiting permeate flux, creating hydraulic resistance, decreasing the lifespan of the membrane, and increasing operation costs (Hubadillah et al., 2022). This accumulation of organic matter, fine particles, or colloidal matter on top of and/or inside membrane pores leads to reversible or irreversible fouling, which makes control strategies or regenerating (cleaning) membranes indispensable for lasting operations (Cai et al., 2023).

Ceramic membranes are characterised by higher mechanical strength, improved chemical resistance, superior thermal stability and longer operational lifetime when compared to polymeric membranes (El-shazly and Fahmy, 2025). However, most commercial ceramic membranes are too expensive by using advanced some high-purity raw materials and energy-intensive processes for preparation (Artun & AŞKIN, 2022). In order to tackle this limitation, many studies have been performed on low cost ceramic membranes which are sourced from widely available natural and agricultural resources. The use of rice husk as a membrane precursor is particularly appealing because rice husk is abundant and widely available agricultural by-product which has high silica content, low density and low cost (El Azizi et al., 2023). Converting rice husk to ceramic membrane materials not only reduces the cost of production, but also conformed with waste valorisation and circular economy.

Rice husk-derived low-cost ceramic membranes show great potential for peat water treatment, as their silica-rich structure could help with membrane rigidity, pore formation, and the filtration performance (Hubadillah et al., 2018). Rice husk ash or rice husk-based ceramic composites can form porous structures suitable for water filtration during membrane fabrication techniques (Susanto et al., 2023). Determination of porosity, pore size distribution, permeability, surface chemistry, and mechanical stability for the resulting membrane has a significant role in the removal efficiency of peat water pollutants (Qi et al., 2025).

But the high-density humic substances in peat water due to hydrophilic and hydrophobic characteristics, can lead to fast filtration membrane with pore blocking, cake layer formation, adsorption of humic substances, and concentration polarisation on membrane surface (Lin et al., 2025).

In order to improve the performance of membranes, especially reduce fouling in direct micro-filtration, pretreatment-assisted membrane filtration has been widely utilised. Physicochemical pretreatment processes (coagulation, adsorption, sedimentation or oxidation) should reduce the organic load and colour intensity as well as suspended particles to be separated in advance before membrane filtration (Elma et al., 2022; Loganathan et al., 2023; Rinaldi et al., 2026; Xia et al., 2021). Pretreatment can enhance the stability of permeate flux, increase pollutant rejection, and prolong membrane operation time by decreasing the foulant concentration reaching the membrane unit (Xie, Fang, et al., 2025; Xie, Liu, et al., 2025). There is, however, still a long way to go on studying the interactions between pretreated peat water components with ceramic membrane surfaces made from rice husks at a molecular level involved in the fouling mechanisms, regeneration behaviour and prediction of long-term performance.

Flux decline behaviour may lead to the fouling analysis using resistance-in-series models as well as evaluation of reversible and irreversible fouling fractions (Huang et al., 2021; Omar et al., 2023; Song et al., 2026). Physical or chemical cleaning can restore the permeability of a membrane to varying degrees depending on the intrinsic fouling mechanism and strength (Gruskevica and Mezule, 2021; Gul et al., 2021). Moreover, the lifetime for a given number of filtration-cleaning cycles is a key parameter that indicates durability, cleaning efficiency, and the maximum replacement time of each membrane (Astrada et al., 2022; El-shazly and Fahmy, 2025; Gruskevica and Mezule, 2021). This analysis is needed to ascertain if the rice husk biozonotropy-derived ceramic membranes can be deployed as a sustainable and cost-effective technology for peat water treatment.

This study aimed to establish the fouling-regeneration mechanisms and lifetime prediction of rice husk-derived low-cost ceramic membranes as pretreatment facility, as well as to create an impact in peat water treatment studies. The study evaluated the membrane performance for permeate flux, pollutant rejection, fouling resistance, regeneration efficiency, and estimated service

life over repeated operational cycles. The novelty of this work came from the integration of developing rice husk-based ceramic membrane, pretreatment-assisted peat water filtration, fouling mechanism analysis, stability test, regeneration assessment, and lifetime prediction. These results are expected to help with a synthesis of novel, inexpensive, and locally available ceramic membranes for sustainable water remediation.

MATERIALS AND METHODS

This study is an experimental investigation to assess the fouling–regeneration mechanisms and to develop a lifetime prediction model of rice husk-derived low-cost ceramic membranes (LCCM) for the pretreatment-assisted peat water treatment. The work was organised into four principal stages: production of activated carbon from rice husk, fabrication and characterisation of tubular ceramic membranes, pretreatment-assisted filtration of peat water, and repetitive fouling–regeneration tests for the prediction of membrane lifetime.

Raw materials and peat water sampling

The membrane was prepared from natural clay, activated carbon from rice husk and Fe_2O_3 powder at 82.5, 15.0 and 2.5 wt.%. The paste was prepared and washed and backwashed with distilled water and the activation of carbon was performed with 2.5 M H_2SO_4 . All solids were ground and screened through 400 mesh. Peat water was taken repeatedly from at least three points in Karang Anyar Village, Sumber Marga Telang District, Banyuasin Regency, South Sumatra, Indonesia. The samples were homogenised before analysis and stored in clean dark containers at low temperature.

Preparation of rice husk-derived activated carbon

The rice husks were washed with distilled water, dried in the sun for 2 days, and carbonised at 400 °C for 4 h. The resulting carbon was ground, sieved to 400 mesh, and immersed in 2.5 M H_2SO_4 for 24 h. The activated carbon was then washed to near neutral pH, oven dried at 300 °C for 2 hours, ball milled for 24 hours, and sieved again to get uniform activated carbon powder.

Fabrication of rice husk-derived ceramic membranes

Dry clay, activated carbon, and Fe_2O_3 were mixed in the mass ratio of 82.5 : 15 : 2.5, and then distilled water was added gradually to give a homogeneous mouldable paste. Tubular membranes with an inner diameter of 5 cm, an outer diameter of 7 cm, a length of 25 cm, and a wall thickness of 1 cm were prepared. The green bodies were dried at room temperature for 7 days and sintered at 900 °C with a heating rate of 5 °C min^{-1} and holding time of 9 h. Membranes were cooled down slowly in the furnace to avoid thermal cracking.

Membrane characterisation

Surface morphology and pore structure were determined by scanning electron microscopy (SEM), and elemental composition and spatial distribution were determined by energy-dispersive X-ray spectroscopy (EDS) and elemental mapping. X-ray diffraction (XRD) and thermogravimetric analysis (TGA) were used to determine crystalline phases and thermal stability respectively. SEM images were converted to black and white and thresholded in OriginPro to identify the pore and solid regions. Apparent porosity (ϕ_{img}) based on the images was calculated as:

$$\phi_{\text{img}} (\%) = (Ap / At) \times 100 \quad (1)$$

where: Ap is the segmented pore area, and At is the total area of the image analysed. Since SEM image analysis is an analysis of two-dimensional surface features, so the result shall be checked by Archimedes water immersion method for improved reliability. The apparent porosity was calculated as:

$$\phi (\%) = \frac{W_s - W_d}{W_s - W_{\text{sub}}} \times 100 \quad (2)$$

where: W_d is the dry mass membrane, W_s is the saturated mass membrane in air and W_{sub} is the suspended saturated membrane.

Pretreatment-assisted peat water filtration system

The raw peat water was stored in a 500 L sedimentation tank and treated sequentially by

sedimentation, slow sand filtration, 5 µm and 1 µm sponge filters, and an activated-carbon filter. The pretreated water was then fed to the tubular membrane at 2 bar and ambient temperature. Permeate was collected at 15, 30, 45, 60, 75, and 90 min. Samples were taken from the raw water, the pretreatment water, and the membrane permeate. The permeate flux (J) and removal efficiency (R) were calculated as:

$$J = \frac{V}{A \times t} \quad (3)$$

$$R (\%) = \frac{C_f - C_p}{C_f} \times 100 \quad (4)$$

where: V is permeate volume, A is effective membrane area, t is filtration time, C_f is the concentration of the feed, and C_p is the permeate concentration.

This equation was used for turbidity, colour, Fe, Mn, nitrite, and other measurable water quality parameters.

Fouling mechanism analysis

Fouling was assessed from the normalised flux (J_t/J_0). Each filtration cycle was terminated at 70% decline of its initial flux value or at the specified cycle time. The total hydraulic resistance was estimated using the resistance-in-series model and Darcy's law:

$$J_n = \frac{J_t}{J_0} \quad (5)$$

$$J = \frac{\Delta P}{\mu R_t} \quad (6)$$

$$R_t = R_m + R_{rev} + R_{irr} \quad (7)$$

where: R_t is the total resistance, R_m is the intrinsic membrane resistance, R_{rev} is reversible fouling resistance, R_{irr} is irreversible fouling resistance, ΔP is transmembrane pressure, and μ is water viscosity.

The flux-decline profile was interpreted as the dominant mechanism: complete, intermediate, or standard pore blocking or cake-layer formation.

Membrane regeneration and flux recovery

Hydraulic backwashing with clean water was applied in the opposite direction of filtration. The flux recovery ratio (FRR), total fouling (F_t),

reversible fouling (F_{rev}), and irreversible fouling (F_{irr}) were calculated as:

$$FRR (\%) = \frac{J_r}{J_0} \times 100 \quad (8)$$

$$F_t (\%) = \left(1 - \frac{J_t}{J_0}\right) \times 100 \quad (9)$$

$$F_{rev} (\%) = \left(\frac{J_r - J_t}{J_0}\right) \times 100 \quad (10)$$

$$F_{irr} (\%) = \left(1 - \frac{J_r}{J_0}\right) \times 100 \quad (11)$$

where: J_r is the flux after backwashing, J_0 is the initial flux and J_t is the flux at the end of the filtration cycle prior to regeneration.

Lifetime prediction of ceramic membrane

Multi-cycle filtration-regeneration predicted the lifetime of the membrane. Each cycle included filtration of peat water, flux measurement, membrane backwashing and flux measurement after regeneration. The experimental design described that the membrane was assumed to be at the end of its useful life when the recovered flux was below 70% of the initial flux. The lifetime decline model was written as:

$$J_n = J_0 e^{-kn} \quad (12)$$

where: J_n is the retrieved flux after the n -th regeneration cycle, J_0 is the initial flux, k is the flux decay constant and n is the number of filtration-regeneration cycles.

When the predicted number of cycles till failure of the membrane was obtained:

$$\frac{J_n}{J_0} = 0.7 \quad (13)$$

Thus

$$n_{life} = \frac{-\ln(0.7)}{k} \quad (14)$$

The operational lifetime in hours was estimated by multiplying the predicted number of cycles by the effective filtration time per cycle:

$$t_{life} = n_{life} \times t_{cycle} \quad (15)$$

where: t_{cycle} is the time to filter one cycle. This allowed quantitatively evaluating the service life of the membrane under repeated filtration and regeneration of peat water.

Analytical methods for peat water quality

Temperature, pH, total dissolved solids, turbidity, colour, Fe, Mn, nitrite, odour, *Escherichia coli*, and total coliform were determined by calibrated meters and standard spectrophotometric or microbiological procedures before pretreatment, after pretreatment, and after membrane filtration. The results were compared to the Indonesian Minister of Health Regulation No 2/2023. All experiments were performed in triplicate and expressed as mean $\pm$ standard deviation.

RESULTS AND DISCUSSION

Characteristics of rice husk-derived ceramic membrane

The tubular membrane geometry consisted of a 5 cm inner diameter, 7 cm outer diameter, 25 cm long, and 1 cm wall thickness filtration zone with an effective filtration area of approximately 0.0393 m² (Figure 1). The geometry was appropriate as it enabled stable collection of permeate and regeneration cycles to be repeated in laboratory-scale continuous peat water filtration.

Morphological and elemental analysis

Figure 1 represents the results obtained from SEM at a $\times 2000$ magnification at three different observation sites to further ascertain the surface morphology, pore distribution, and uniformity of the rice husk-derived ceramic membrane.

SEM micrographs at 2000X magnification suggest the heterogeneous surface morphology of rice husk-derived ceramic membrane. Surface showed irregular agglomerates of clay basis, layered structures, and several interconnected voids, suggesting incomplete rearrangement of particles during sintering at observation point 1 (Figure 2a). Observation point 2 (Figure 2b) presented a more open and very porous structure with many cavities and fine granular particles scattered in the ceramic matrix. These features are consistent with pore formation from thermal decomposition of rice husk-derived activated carbon (Igboko et al., 2025). The scattered bright particles could be Fe-containing phases (Yousefi et al., 2022). Conversely, point 3 (Figure 2c) pointed out a relatively dense and consolidated zone with fewer small pores, although several larger voids and local microcracks were observed.



Figure 1. Photographic appearance rice husk-derived low-cost ceramic membrane

The difference between the three observation points suggests that the membrane has a mixed pore structure with open transport channels and compact load-bearing regions. The porous areas are expected to enhance the permeation of water and provide adsorption sites for dissolved organic matter, suspended solids, and coloured humic substances in peat water. However, the rough surface, irregular pore entrances, and interconnected cavities may cause foulant deposition and pore blockage during long-term filtration (Jang et al., 2024; Nędzarek and Mitkowski, 2022). In contrast, the denser zones can increase the mechanical stability and resistance to repeated backwashing (Y. Zhang et al., 2023). Thus, the heterogeneous microstructure provides a functional compromise between permeability, contaminant retention, and structural durability, and is responsible for the observed progressive flux decline as well as partial flux recovery during repeated fouling–regeneration cycles (Oyekanmi et al., 2022).

Energy Dispersive Spectroscopy assays and the elemental mapping were performed to determine the composition and distribution of major elements in rice-husk-derived ceramic membrane, as shown in Figures 3 and 4.

EDS analysis verified that the O (26.8 wt. %), Fe (17.7 wt. %), Si (12.0 wt. %), Al (6.1 wt. %), and C (5.9 wt. %) as its main elemental components (Figure 3). The dominance of O, Si, and Al proven the formation of an aluminosilicate framework originated from clay itself and the presence of carbon confirmed that rice husk-derived activated carbon is present as well. The

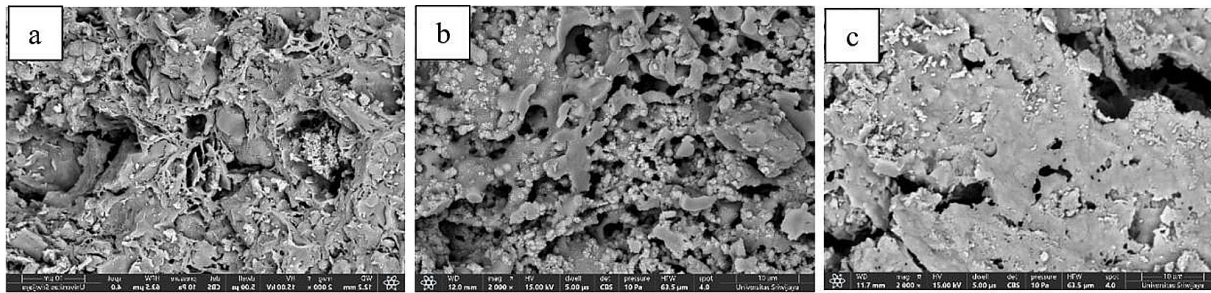


Figure 2. SEM micrographs of the rice husk-derived ceramic membrane at three observation points with $\times 2000$ magnification (a) point 1, (b) point 2, (c) point 3

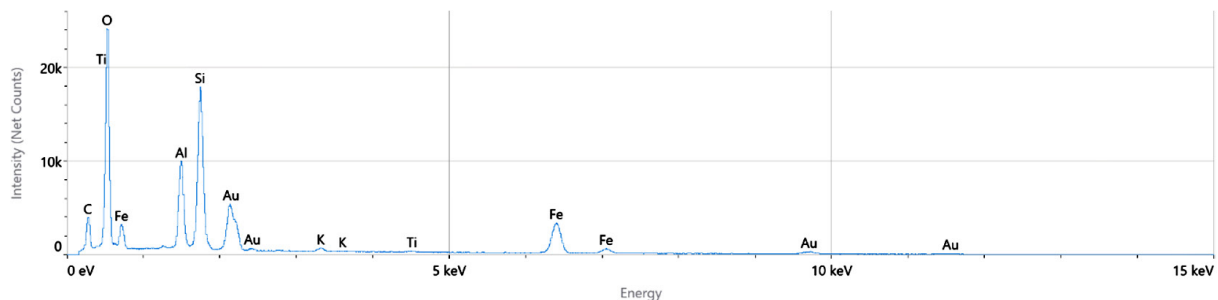


Figure 3. Energy dispersive spectroscopy (EDS) spectrum of the rice husk-derived ceramic membrane

dominance of O, Si, and Al proven the formation of an aluminosilicate framework originated from clay itself and the presence of carbon confirmed that rice husk-derived activated carbon is present as well (Khaer et al., 2026; Nahar et al., 2020). As a result, the moderate Fe content proved that Fe powder was successfully held in the ceramic matrix (Susanto et al., 2023). The MgO contents in Minor K and Ti plates were 0.5 and 0.2 wt %, respectively, and were due to naturally occurring mineral constituents of the raw materials. The Au signal was linked to the conductive coating during SEM preparation, so it is not included in the membrane composition.

The elemental mapping demonstrated that O, Si, and Al were widely distributed across the membrane surface, suggestive of a planar and comparatively convoluted clay-based network (Figure 4). The carbon was distributed throughout the porous network, potentially providing adsorption sites for humic substances and other dissolved organic compounds in peat water (Said et al., 2025). In contrast, the Fe was dispersed around the entire field of view, but was locally enriched in some areas, consistent with partial agglomeration of particles. A mixture of activated carbon and Fe-containing phases can contribute to contaminant retention due to adsorption and surface interactions, whereas the

aluminosilicates act as a structural matrix for multiple filtration-backwashing applications (Nahar et al., 2020). Yet, localised regions of carbon and iron will tend to promote organic-foulant accumulation, leading to partial flux recovery in subsequent regeneration cycles, thus increasing operational-exposure duration, affecting the lifetimes of these membranes (Qadafi et al., 2023).

Porosity analysis and validation

The pore distribution seen in SEM micrographs was analyzed through OriginPro at three different observation points, and the quantitative porosity maps are shown in Figure 5.

These image-based porosity values were then compared against the Archimedes method using the dry, saturated, and suspended membrane masses, as shown in Table 1, to validate the findings.

The image analysis of OriginPro showed that the pore distribution was heterogeneous at all three observation points of the membrane, with 49.204, 54.143, and 40.645% porosity at points 1, 2, and 3 (Figure 5). These quantitative results are in agreement with the pseudo-colour maps, with point 2 exhibiting the most extensive pore-rich regions and point 3 having a comparatively denser and less porous structure, while point 1 showed an intermediate morphology. The spatial variation

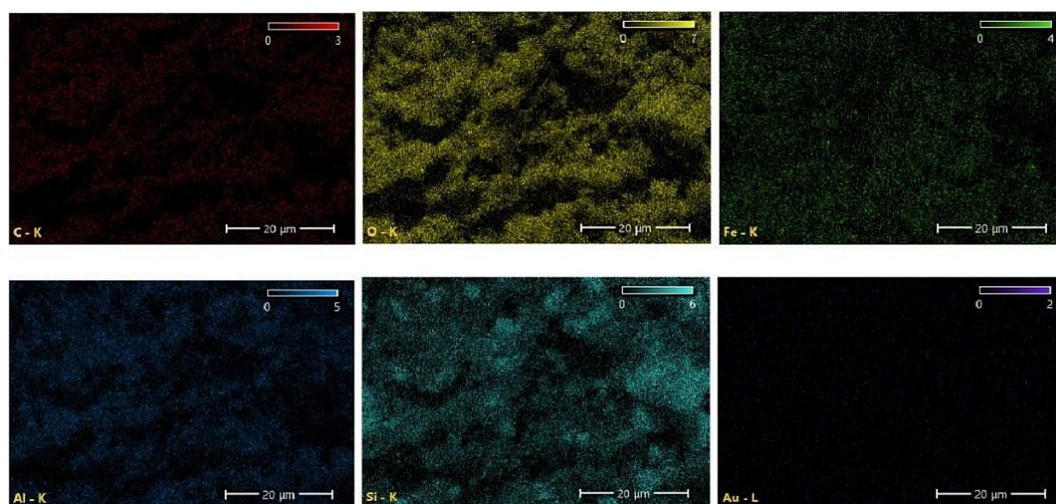


Figure 4. Elemental mapping of the rice husk-derived ceramic membrane showing C, O, Fe, Al, and Fe distribution

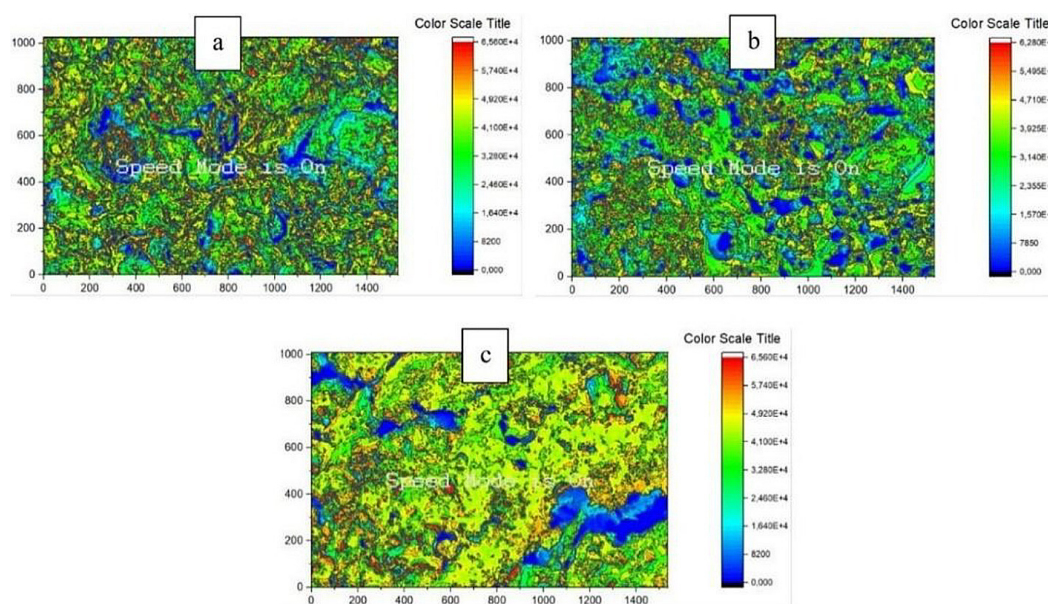


Figure 5. OriginPro-based porosity maps of the rice husk-derived ceramic membrane at different observation points: (a) point 1; (b) point 2; (c) point 3

Table 1. Comparison of membrane porosity determined using OriginPro image analysis and Archimedes method

Point	OriginPro porosity (%)	Dry mass, W_d (gr)	Saturated mass, W_s (gr)	Suspended mass, W_{sub} (gr)	Archimedes porosity (%)	Absolute difference (%)
1	49.204	501.00	731.15	261.15	48.968	0.236
2	54.143	498.50	753.36	282.26	54.099	0.044
3	40.645	502.00	692.93	223.94	40.712	0.067
Mean	47.997				47.927	0.071

implies non-uniform packing of the particles and formation of pores in the clay-rice husk activated carbon-iron matrix, possibly due to variations in carbon distribution, local agglomeration, and

thermal decomposition during the sintering (El Azizi et al., 2023; Y. Zhang et al., 2026).

Table 1 shows that the Archimedes method gave porosities of 48.968, 54.099, and 40.712%

respectively, with absolute differences of just 0.236%, 0.044%, and 0.067%. Both methods gave the same mean porosity of 47.997%, and the mean absolute difference was 0.071%, confirming the reliability of the image-analysis method with OriginPro. The mean porosity is moderately high, which is favourable for the permeation of peat water and makes sites for the adsorption of organic contaminants accessible (Elma et al., 2022). Highly porous regions may favour foulant penetration and internal pore blockage, while denser regions may limit flow but enhance structural resistance during backwashing (Maury Njoya et al., 2025; Xie, Fang, et al., 2025). This heterogeneous pore architecture thus provides an insight into the trade-off between permeability, fouling development, regeneration efficiency, and the operational lifetime of the membrane.

X-Ray diffraction analysis

X-ray diffraction (XRD) was used to examine the crystalline-phase composition of rice husk-derived ceramic membrane, and the corresponding diffraction pattern is shown in Figure 6.

The XRD pattern displayed a dominant sharp peak at around $2\theta = 26\text{--}27^\circ$ and smaller peaks near 21° , 37° , 50° , and between 60 and 68° for the ceramic membrane derived from rice husk, as shown in Figure 6. The extremely high peak was primarily assigned to crystalline silica, particularly quartz, contributed from the clay and the rice husk-derived silica-rich precursor. An amorphous aluminosilicate phase and a carbonaceous phase were apparent in the broad background

between 15° and 40° . The secondary reflections, however, may be related to the residual clay minerals and the iron-bearing crystalline phases generated by thermal oxidation of Fe powder introduced in the membrane during sintering (Khalil et al., 2024).

The presence of crystalline silica, amorphous carbon, aluminosilicate phases, and iron-containing compounds further affirms the multifunctional nature of the membrane. The crystalline silica and ceramic phases ensure the dimensional stability and mechanical resistance to repeated filtration and backwashing, while the amorphous carbon fraction provides adsorption sites for humic substances and other organic pollutants contained in peat water (Elfiana et al., 2022; Hakami et al., 2020). Surface complexation or electrostatic attraction between dissolved organic matter and iron-containing phases further enhances the interactions. On the other hand, because of the heterogeneous mineral structure, sites for preferential adsorption and foulant accumulation can also be created that will lead to gradual pore blockage, incomplete recovery of membrane flux after backwashing, and a decrease in membrane performance along with consecutive fouling–regeneration cycles (Kenari et al., 2025; Gruskevica and Mezule, 2021).

Thermogravimetric analysis (TGA)

The thermal stability and mass-loss behaviour of the ceramic membrane obtained from rice husk during heating were investigated by thermogravimetric analysis (TGA), as shown in Figure 7.

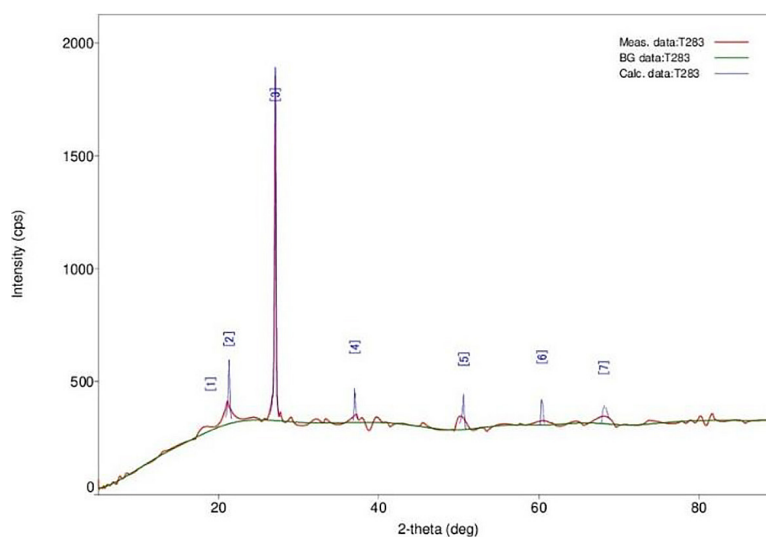


Figure 6. The X-ray diffraction pattern of rice-husk-derived ceramic membrane after heating at 900°C

Figure 7 shows the TGA profile revealed two major stages of mass loss and high thermal stability of the rice husk-derived ceramic membrane. The first stage presented a mass loss of around 1.76% in the heating and holding at around 100 °C, mainly due to the removal of physically adsorbed water and low molecular weight volatile compounds. Further slow mass loss (2.77%) was observed during the heating between ~100 and 700 °C, which could be explained by the clay dehydroxylation and the decomposition of remaining organic functional groups in the rice husk-derived activated carbon. The lack of a sharp degradation step reflects a good integration of the carbonaceous and iron-containing components in the clay-based ceramic matrix (Nahar et al., 2020).

The residual mass of the membrane at 700 °C was 95.29%, indicating a total mass loss of only about 4.71%. This high residue is due to the presence of thermally stable inorganic aluminosilicate, silica, and iron-containing phases (Bahrouni et al., 2025). The thermal resistance is beneficial for membrane regeneration as the structure is expected to withstand repeated drying, thermal cleaning, and operational temperature changes without significant degradation of the material (Lagdali et al., 2026). However, the slow decomposition of the residual carbonaceous fraction at high temperature indicates that excessive thermal regeneration should be avoided so as to preserve adsorption sites and maintain long-term permeability, contaminant

retention, and membrane life (Hakami et al., 2020; Malebadi et al., 2025).

Initial peat water quality and pretreatment performance

This study compared the physicochemical and microbiological characteristics of raw peat water with those after each pretreatment unit, as well as with the final membrane permeate, in order to evaluate the performance of each treatment stage. Table 2 summarises the change of odour, pH, TDS, turbidity, colour, nitrite, Fe, Mn, *E. coli*, and *total coliform* along with overall removals and water-quality standards applicable.

Table 2 shows that the contaminant load entering the ceramic membrane was significantly reduced in sequential pretreatment stages. Sedimentation reduced turbidity from 81.6 to 46.7 NTU and TDS from 549 to 327 mg/L, leading to the effective removal of settleable particles and particulate-associated contaminants. The best turbidity, colour, Fe, and Mn levels reached after slow-sand filtration were 17.9 NTU, 48.1 TCU, 3.58 mg/L, and 0.37 mg/L, respectively. The retention of fine suspended particles was demonstrated by subsequent filtration through the 5 and 1 µm sponge filters, which reduced turbidity to 7.6 NTU and nitrite to a concentration of 0.18 mg/L. The use of activated-carbon filtration led to further reductions of colour, odour, TDS, and dissolved substances, obtaining water with 13.4 TCU, 260 mg/L TDS, with

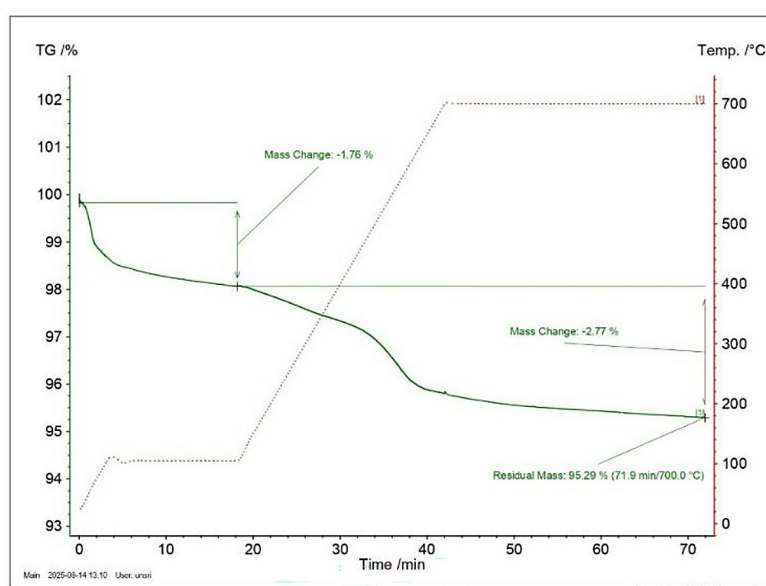


Figure 7. Thermogravimetric profile of the rice husk-derived ceramic membrane up to 700 °C

Table 2. Changes in peat water quality during pretreatment and rice husk-derived ceramic membrane filtration

Parameters	Unit	Raw peat water	After sedimentation	After slow-sand filtration	After 5 and 1 µm sponge filters	After the activated carbon	After the ceramic membrane	Overall removal (%)	Standard
Door	-	Strong earthy/peat odour	Moderate odour	Slight earthy odour	Slight earthy odour	Odorless	Odorless	-	Odorless
pH	-	4.41	4.62	4.49	4.73	5.84	6.83	-	6.5–8.5
TDS	mg/L	549	327	310	300	260	214	61.02	<300
Turbidity	NTU	81.6	46.7	17.9	7.6	4.4	0.92	98.87	<3
Colour	TCU	64.8	64.1	48.1	31.5	13.4	5.8	91.05	10
NO ₂	mg/L	1.17	1.09	0.93	0.18	0.03	0.001	99.92	3
Fe	mg/L	6.01	4.73	3.58	2.06	1.31	0.12	98.00	0.2
Mn	mg/L	0.69	0.54	0.37	0.26	0.15	0.02	97.10	0.1
<i>E. coli</i>	CFU/100 ml	8.7	2.1	1.45	2.4	2	0	100	0
Total coliform	CFU/100 ml	14.5	6.8	4.65	1.50	1.08	0	100	0

no detection of odour. The small changes in pH and the transient increase of *E. coli* after sponge filtration could be due to sampling variances, redistribution of retained microorganisms, or detachment from the filtration media, resulting in high local concentrations of bacteria during filtration rather than reflecting a long-term deterioration in water quality (Ciawi and Khoiruddin, 2024; Kendarto et al., 2019).

The ceramic membrane, which was derived from rice husk, was the polishing step, but had the greatest overall positive impact on the quality of water. Then, the pH was raised to 6.83, which is within the acceptable range (6.5–8.5), and TDS dropped down to 214 mg/L, while turbidity and colour were reduced to 0.92 NTU and 5.8 TCU for overall removal efficiencies of about 98.87% and 91.05%, respectively, after the membrane filtration stage. The membrane also reduced Fe, Mn, and nitrite to 0.12, 0.02, and 0.001 mg/L with removal efficiencies of 98.00%, 97.10%, and 99.92%. The microbiological component of zero detectable organisms was satisfied by the complete removal of *E. coli* and *Total coliform*. The results illustrate that the activated pretreatment was effective in achieving substantially reduced initial fouling loads, while final removal with the ceramic membrane occurred via a combination of size exclusion, pore retention, surface adsorption, and drinking (residual contaminants remaining trapped) within the membrane structure (Foorginezhad et al., 2025; Zhou et al., 2023).

Fouling mechanism analysis

Table 3 shows the reproducibility of the multi-cycle flux profiles under constant transmembrane pressure (2 bar). The peat water flux at the beginning of cycle 1 was 413,81 L/m².h and decreased to 319,81 L/m².h in cycle 6, which is a cumulative retention of 77,28%. Filtration in cycles 1–5 resulted in a terminal decline of 29.6–30.2% (almost constant), while cycle 6 achieved a decline of 26.73% in the available 13 h testing period. Most notably, the duration to reach the operating limit was reduced from 77 h in Cycle 1 to 13 h in Cycle 6, and the average flux-loss rate increased from 1.61 to 7.12 L/m².h. The trends suggest that backwashing re-established the main flow pathways but did not completely remove deposits held in constricted pores or strongly adsorbed to the clay-carbon-iron surface (Cai et al., 2023; Gruskevica and Mezule, 2021).

Figure 8 shows the first cycle (cycle 1). This long initial phase for reaching the operating threshold was followed by shorter periods of filtration, each progressively more compressed to occupy a maximum of 77, 38, 30, 22, 18, and finally only 13 h until approaching an operating threshold, 83.1% reduction in time from cycle-1 to cycle-6. The profile was not completely monotonic as small flux rebounds developed through a few cycles during transient rearrangement, detachment, or compaction of deposited solids. However, the overall envelope for downward action was above reproach. In humic-enriched waters, such flux loss is often considered to reflect a combination of

Table 3. Hydraulic performance of ceramic membrane derived rice husk during six filtration backwash cycles

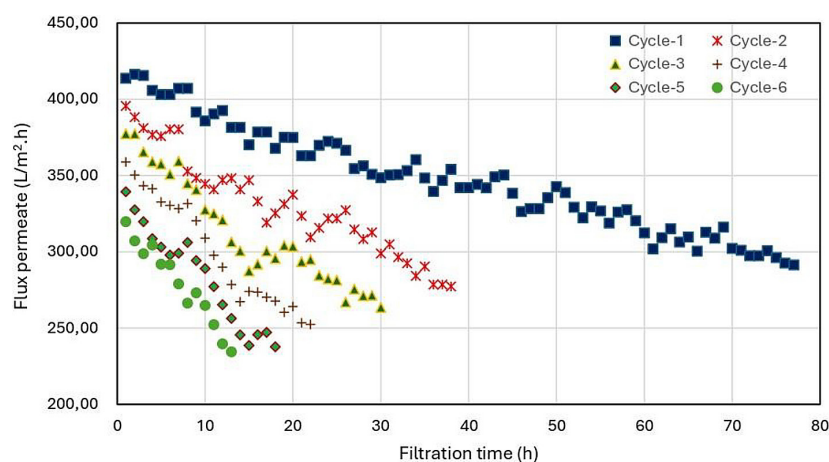
Cycle	Time (h)	Initial flux, J_o (L/m ² .h)	Final flux, J_{end} (L/m ² .h)	Flux decline (%)	Flux recovery (%)	Average rate (%)
1	77	413.81	291.32	29.60	100	1.61
2	38	395.60	277.32	29.90	95.60	3.20
3	30	377.41	263.43	30.20	91.20	3.93
4	22	358.91	252.31	29.70	86.73	5.08
5	18	339.40	237.68	29.97	82.02	5.98
6	13	319.81	234.34	26.73	77.28	7.12

size exclusion with those particles unable to pass through the pore throat, adsorption, but also dynamic interactions with sediment grains whereby pore constriction and plugging take place, as well as deposition of an organic-depleted surface layer (Kallapalli and Basu, 2025; Yang et al., 2021). Similar cooperativity of pore blocking and surface-layer formation has been observed in the filtration of aquatic humic matter through ceramic membranes as well (X. Zhang et al., 2018).

Each cycle was fitted to the classical Hermia models separately. The top fits consisted of standard blocking for cycles 1 and 2, cake filtration during cycle 3, intermediate blocking during cycle 4, and complete blocking for cycles 5 and 6 (Figure 9). The differences between the highest and second-highest R^2 values, however, were small (between 0.0002 and 0.0056). When interpreting these results, one should be aware that they must not be interpreted as six tightly compartmentalized mechanisms. Rather, they suggest a developing and heterogeneous type of fouling regime. This interpretation is in line with the established empirical phenomenon that in the scenarios where several models provide almost equal fits, a Hermia

mechanism can only be assigned to one of them (Shanmathi et al., 2025). Pereira et al., (2023) pointed out that R^2 values close together often correspond to blocking processes that overlap, and not necessarily to a single mechanism.

Linearized Hermia analysis resulted in high coefficients of determination for the four blocking models, indicating that the observed flux decline could not be attributed to a single ideal mechanism. Figure 9 shows that the R^2 values were highest in cycles 1 and 2 for standard blocking, in agreement with the deposition of humic matter and fine particles over time on the pore walls. Cycle 3 was mainly dominated by cake filtration, cycle 4 by intermediate blocking, and cycles 5 and 6 by complete blocking (albeit marginally). The differences between the fitted R^2 values were small, and so the best way to interpret the results is as a mixed and evolving fouling process. Internal pore constriction dominated the early operation, and the accumulated residual matter subsequently promoted surface-layer formation and obstruction of the remaining active pores (Sheng et al., 2025). The heterogeneous pore network of rice

**Figure 8.** Permeate flux decline during six consecutive filtration backwash cycle at 2 bar

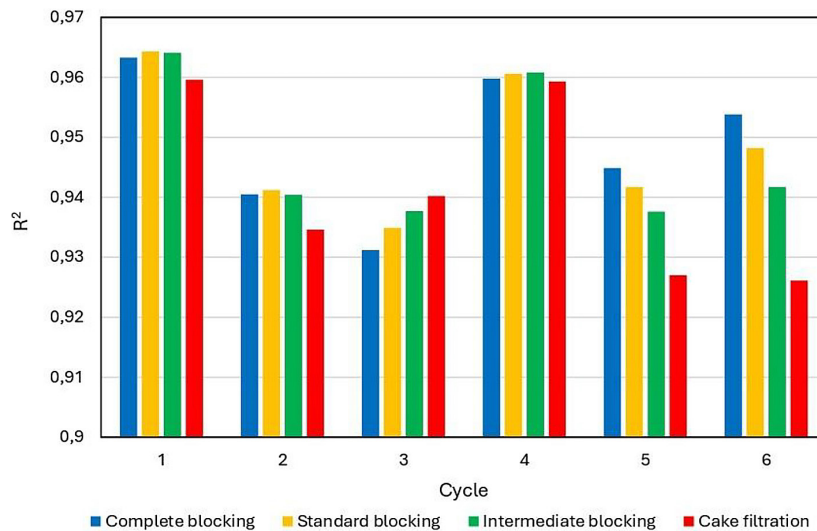


Figure 9. R^2 statistics of the classical Hermia fouling model for each cycle

husk activated carbon, combined with adsorption on carbonaceous and iron-containing sites, may improve peat-water purification but also increases the chance of organic foulant retention (Qiao et al., 2024).

Membrane regeneration and flux recovery

Hydraulic backwashing recovered most of the cycle-specific flux, but its effectiveness decreased slightly with repeated use. Table 4 shows the cycle-to-cycle flux recovery ratio decreased from 95.60% after cycle 1 to 94.23% after cycle 5. It was found that about 24.20–25.30% of the initial flux was due to reversible fouling and could be recovered by backwashing, while the irreversible part increased from 4.40% to 5.77%. The recovered starting flux decreased gradually from 413.81 to 319.81 L/m².h in the six cycles. The increasing irreversible contribution indicates the cumulative adsorption, narrowing and compaction of the pores of organic deposits that were not fully detached by hydraulic shear (Mei et al., 2023; Sisay et al., 2023).

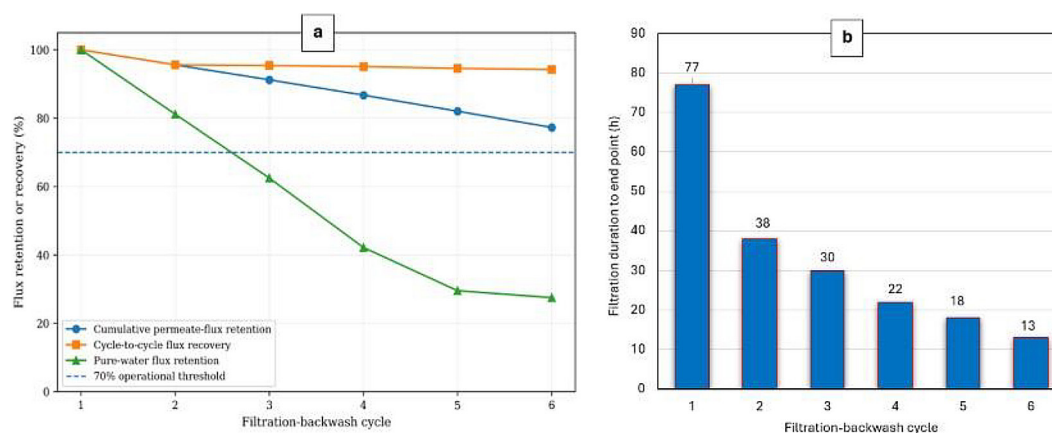
Figure 10a, showing the distinction between process-flux recovery and intrinsic hydraulic recovery was evident from the pure-water measurements. Pure-water flux decreased from 1237.96 to 340.27 L/m².h, leaving only 27.49% of its initial value after cycle 6, while the cycle-start permeate flux still retained 77.28%. Compared to the virgin membrane, pure water flux diminished to 81.16, 62.47, 42.16, 29.52, and 27.49% of its initial value after the first through fifth regeneration, as shown

in Figure 10a. This stronger loss in pure-water permeability suggests that internal pore accessibility was progressively reduced even though backwashing maintained a substantial fraction of the operational permeate flux (Chen et al., 2025; Nilusha et al., 2020). The results support the use of routine hydraulic backwashing for short-term recovery, but periodic intensified cleaning would be required to remove strongly retained humic substances and preserve the intrinsic permeability of the clay-activated-carbon-iron matrix (Gruskevica and Mezule, 2021).

The progressive fouling accumulation was also mirrored in the shortening of the filtration duration, as shown in Figure 10b. The time of operation was reduced significantly from 77 h in the first cycle to 38, 30, 22, 18 and 13 h in cycles 2–6, amounting to an overall reduction of about 83%. Backwashing recovered the permeate flux temporarily but the remaining irreversible resistance caused the critical flux loss condition to be reached earlier in the subsequent cycles. These results confirmed that the membrane performance was controlled by a combination of reversible surface deposition and cumulative irreversible fouling within the pore network (Xie et al., 2025). Thus, the hydraulic backwashing was enough to recover the flux in short term of rice husk derived ceramic membrane but not enough to maintain the permeability of the membrane in long term. Periodic chemical or chemically assisted cleaning, optimisation of backwashing intensity and improvement of peat-water pretreatment are needed to extend the effective lifetime of the membrane

Table 4. Backwash recovery and fouling fractions calculated from successive cycle fluxes

Cycle	J_o (L/m ² .h)	J_{end} (L/m ² .h)	J_r (L/m ² .h)	FRR (%)	F_t (%)	F_{rev} (%)	F_{irr} (%)
1	413.81	291.32	395.60	95.60	29.60	25.20	4.40
2	395.60	277.32	377.41	95.40	29.90	25.30	4.60
3	377.41	263.43	358.91	95.10	30.20	25.30	4.90
4	358.91	252.31	339.40	94.57	29.70	24.27	5.43
5	339.40	237.68	319.81	94.23	29.97	24.20	5.77

**Figure 10.** The performance regeneration: (a) cumulative amount of recovered peat-water flux and pure-water permeability; (b) duration time for each cycle filtering

and reduce the organic matter loading (Hakami et al., 2020; Nilusha et al., 2020).

The results suggest that hydraulic backwashing is suitable for maintenance cleaning but insufficient as a sole long-term regeneration method. Compared with the majority of polymeric membranes, ceramic membranes resist harsher cleaning conditions and therefore periodic chemically enhanced backwashing or cleaning-in-place can effectively remove adsorbent organic foulants that are resistant to hydraulic shear (Elfiana et al., 2022; Xie et al., 2025). The immediate rise of irreversible resistance after cycles 2–3 clearly delineates this period in the lifecycle of the present membrane as a technically sound juncture during which an intensified cleaning step may be introduced, contingent upon characterisation confirming that both chemical compatibility with and structural stability of its ceramic body derived from rice husk are satisfied.

Life time prediction of ceramic membrane

Figure 11 shows the exponential decay of normalised recovered flux with increasing number of regeneration cycles and its intersection with the pre-set end-of-life threshold of 70% of the

initial recovered permeate flux. The modelling approach provides a practical basis for predicting when membrane performance becomes operationally unacceptable and to set up an appropriate cleaning, replacement, or regeneration schedule. An empirical exponential decay model was constructed to quantitatively assess the long-term performance and identify the operational end-of-life of the rice husk-derived ceramic membrane by using the flux recovery after repeated filtration–backwashing cycles. The model parameters and lifetime estimates are summarised in Table 4, which includes the decay equation, goodness of fit, operational threshold, predicted end-of-life cycle, and estimated operating time.

Figure 11 shows a systematic exponential reduction of the normalised recovered peat-water flux with the increasing filtration–backwashing cycles. The experimental data were well described by $J_n/J_0 = \exp[-0.0498(n-1)]$, with a flux decay constant of 0.0498 per cycle and a high coefficient of determination ($R^2 = 0.9958$). The good agreement between the observed data and the exponential model indicates that the exponential model is a valid model to describe the cumulative deterioration of membrane performance under the operating conditions explored (Kim et al., 2020). The initial

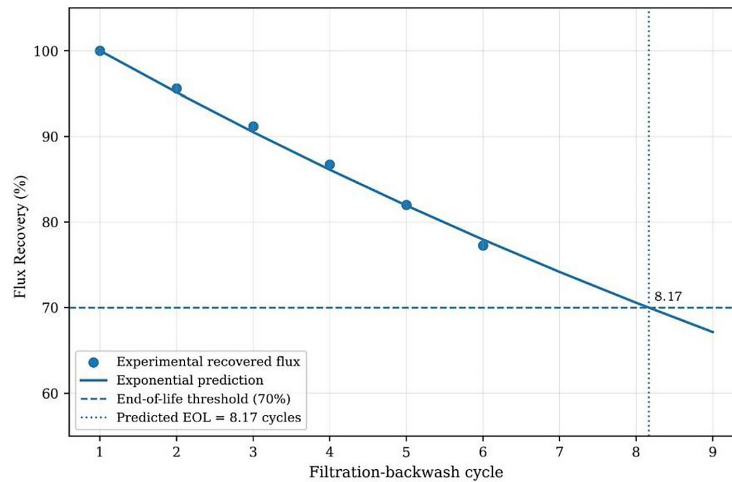


Figure 11. Exponential life-time model based on the recovered peat-water flux and 70% end-of-life threshold

flux of the recovered peat-water was 413.81 L/m².h, and the loss of recoverable performance of the membrane was 4.9% per cycle. Although hydraulic backwashing restored a large proportion of the permeate flux after each filtration period, the continuous reduction in recovered flux suggests that regeneration was incomplete. The deterioration was likely associated with the progressive accumulation of irreversible fouling through organic-matter adsorption, internal pore blocking, and consolidation of deposits within the heterogeneous pore structure of the clay–rice husk activated carbon–iron ceramic membrane (Gruskevica and Mezule, 2021; Hakami et al., 2020).

As summarised in Table 5, the operational end-of-life was set as a decrease in recovered flux to 70% of the initial flux. The model predicts that this threshold will be reached after 8.17 regeneration cycles with predicted flux retentions

of 70.58% and 67.15% at Cycles 8 and 9, respectively. Therefore, the practical end of life point is between the two cycles, which indicates that intensive cleaning, membrane replacement or better pretreatment process should be adopted before the ninth cycle. Based on the observed cumulative filtration time of 198 h through Cycle 6, the estimated operational lifetime was 211 h, or approximately 38.5 h of additional filtration to meet the end-of-life criterion. These results demonstrate that the empirical model is a useful tool for establishing preventive maintenance and regeneration schedules (Tian et al., 2026). However, additional long-term testing is required to validate the model and improve its reliability for continuous or larger-scale applications since the lifetime estimate was extrapolated from six experimental cycles (Lv et al., 2023). This testing should be conducted under different peat-water characteristics, trans-membrane pressures, and cleaning conditions (Dzihora and Stolyarenko, 2022).

Table 5. Parameters and prediction of exponential membrane life-time model

Parameter	Estimated value
Initial recovered peat water flux	413.81 L/m ² .h
Recovered flux model	$J_n/J_0 = \exp[-0.0498(n-1)]$
Flux decay constant, k	0.0498 /cycle
Model coefficient of determination, R ²	0.9958
End of life criterion	$J_n / J_0 = 0.70$
Predicted end of life, n_{life}	8.17 regeneration cycles
Predicted retention at cycle 8	70.58%
Predicted retention at cycle 9	67.15%
Observed filtration time through cycle 6	198 h
Estimated operational lifetime	211 h

Peat water quality after regeneration

The physicochemical and microbiological characteristics of raw peat water and the permeate after six consecutive membrane-regeneration cycles are summarised in Table 5. The quality of treated-water was examined against the permissible limits stipulated in Indonesian Minister of Health Regulation No. 2 of 2023 to identify the effect of repeated regeneration on the membrane's treatment effectiveness. Comparison of pH, TDS, turbidity, colour, ammonia, iron, manganese, E. coli and total coliform provides an indication of the ability of the membrane to maintain permeate

Table 6. Peat water quality after membrane regeneration

Parameters	Unit	Raw peat water	After cycle 1	After cycle 2	After cycle 3	After cycle 4	After cycle 5	After cycle 6	Standard
odour	-	Strong earthy/peat odour	Odourless	Odourless	Odourless	Odourless	Odourless	Odourless	Odourless
pH	-	4.41	6.83	6.77	6.73	6.76	6.68	6.63	6.5–8.5
TDS	mg/L	549	214	232	229	237	242	249	<300
Turbidity	NTU	81.6	0.92	1.15	1.21	1.18	1.39	1.57	<3
Colour	TCU	64.8	5.8	6.3	6.7	7.5	8.2	8.9	10
NO ₂	mg/L	1.17	0.001	0.003	0.004	0.003	0.005	0.006	3
Fe	mg/L	6.01	0.12	0.14	0.15	0.14	0.17	0.19	0.2
Mn	mg/L	0.69	0.02	0.04	0.03	0.05	0.05	0.06	0.1
<i>E-coli</i>	CFU/100 ml	8.7	0	0	0	0	0	0	0
Total coliform	CFU/100 ml	14.5	0	0	0	0	0	0	0

quality throughout prolonged filtration–back-washing operation.

Table 6 shows that the pretreatment-assisted rice husk-derived ceramic membrane significantly improved the physicochemical quality of peat water in six filtration–regeneration cycles. The strong earthy smell of raw water was completely removed, and its pH value was increased from an acidic pH of 4.41 to 6.63–6.83, which is still in the permissible range of 6.5–8.5. TDS reduced from 549 mg/L to 214–249 mg/L and turbidity from 81.6 NTU to 0.92–1.57 NTU. Similarly, the colour effect was the decrease from 64.8 TCU to 5.8–8.9 TCU, reflecting an effective retention of suspended particles, colloidal material, and chromophoric peat-derived organic compounds. Although the TDS, turbidity, and colour gradually increased during the later regeneration cycles, all values remained below the limits specified in Indonesian Minister of Health Regulation No. 2 of 2023. This minor deterioration is consistent with the progressive development of irreversible fouling and residual pore blockage, which can lead to a decrease in adsorption capacity and enable limited solute passage after multiple filtration–backwashing operations (Yang et al., 2021; Zuo et al., 2020).

The membrane system also exhibited efficient removal of inorganic and microbiological contaminants after regeneration. The raw-water concentrations of NO₂⁻, Fe, and Mn were reduced from 1.17, 6.01, and 0.69 mg/L to 0.001–0.006, 0.12–0.19, and 0.02–0.06 mg/L, respectively. The increases in Fe and Mn concentrations in the last periods indicated a progressive

saturation of the adsorption sites and the decline of the retention performance (Astrada et al., 2022), but the final Fe and Mn concentrations did not exceed the regulatory limits of 0.2 mg/L for Fe and 0.1 mg/L for Mn. Furthermore, *E. coli* and *total coliform* were reduced from 8.7 and 14.5 CFU per 100 mL in raw peat water to non-detectable levels in every cycle, meeting the zero-detection microbiological requirement. The constant permeate quality confirms that the membrane retention function was maintained during repeated hydraulic regeneration despite the observed decrease in recovered flux and filtration duration (Elfiana et al., 2022). Membrane end-of-life should therefore be defined not only by water-quality compliance but also by hydraulic productivity, energy demand, and the increasing frequency of regeneration required during long-term operation (Lv et al., 2023).

CONCLUSIONS

The low-cost ceramic membrane derived from rice husk, consisting of natural clay, rice husk activated carbon, and Fe₂O₃, showed appropriate structural and functional characteristics for pretreatment-assisted treatment of peat water. The heterogeneous porous structure with an average porosity of about 47.927% offered enough water-transport pathways and adsorption sites while maintaining structural and thermal stability. The integrated treatment system effectively improved the peat water quality with a reduction of turbidity, colour, Fe, Mn, and

nitrite by 98.87%, 91.05%, 98.00%, 97.10% and 99.92%, respectively. It also completely eliminated detectable *E. coli* and total coliform, and the final pH and other physicochemical parameters were in compliance with the applicable water-quality standards.

The flux-decline analysis indicated that the membrane fouling occurred through mixed and gradually evolving mechanisms instead of one ideal Hermia mechanism. The first filtration cycles were dominated by internal pore constriction with the formation of a cake layer, intermediate blocking, and more complete pore blocking in the later cycles. Hydraulic backwashing was found to recover most of the permeate flux specific to the cycle, and the flux recovery ratio slightly decreased from 95.60% to 94.23%. However, the irreversible fouling was increased from 4.40% to 5.77%, the retained pure-water permeability was decreased to 27.49% of the initial value, and the filtration time was decreased from 77 h in cycle 1 to 13 h in cycle 6. These findings demonstrate that hydraulic backwashing is effective for short-term maintenance but is not sufficient for complete removal of strongly adsorbed organic matter and deposits retained within the heterogeneous pore network.

The decrease of recovered permeate flux was well described by the exponential model ($J_n/J_0 = e^{[-0.0498(n-1)]}$) with ($R^2 = 0.9958$). Using 70% of the initial recovered flux as the operational end-of-life criterion, the membrane lifetime was predicted to be 8.17 filtration–regeneration cycles, corresponding to approximately 211 h of operation under the investigated conditions. The quality of the treated water remained within the required limits for the duration of six cycles, but the gradual loss of hydraulic productivity suggests that the lifetime of the membrane should be assessed considering the compliance with the water quality requirements, the recovery of the flux, the duration of filtration, and the frequency of regeneration. Therefore, it is recommended to perform periodic chemically enhanced cleaning, to improve pretreatment and optimise backwashing conditions to reduce the irreversible fouling and prolong the membrane service life. Further long-term and pilot-scale experiments are required to validate the proposed lifetime model under different compositions of peat-water and operational conditions.

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