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From biomass to clean water: Sustainable integration of low cost ceramic membranes for peat water treatment

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ABSTRACT

This study investigated the application of low cost ceramic membranes produced from rice husk, bamboo, palm shell, coconut shell and empty fruit bunches (EFB) for the treatment of peat water. Ceramic membranes were produced by mixing biomass-derived activated carbon, clay, and iron powder, followed by sintering at 900 °C. The membranes were analyzed using SEM, EDS, XRD, and TGA, demonstrating advantageous thermal stability, mechanical strength, and selectivity. On the basis of the characterization results, the EFB membrane demonstrating the most favorable performance was selected for evaluation in peat water treatment. Filtration experiments demonstrated that the ceramic membranes generated from EFB markedly enhanced water quality, decreasing TDS from 549 mg/L to 170.1 mg/L, turbidity from 8.52 NTU to 2.65 NTU, and color from 64.8 TCU to 8.3 TCU, all conforming to clean water requirements. Subsequent to polishing, the water quality conformed to drinking water regulations, with TDS diminished to 27.9 mg/L, turbidity to 1.50 NTU, and color to 5.3 TCU, while *E. coli* and *coliforms* were eradicated. Furthermore, the concentrations of Fe and Mn were diminished by more than 98%. The pH was effectively modified from 4.41 to 7.2, making the water suitable for ingestion. The findings suggest that EFB-based ceramic membranes offer a sustainable and cost-effective alternative for decentralized water treatment in peatland environments. This research advances the circular economy by employing agricultural waste, offering an innovative and scalable alternative for the production of clean and potable water in rural areas with restricted access to safe water.

Keywords: low cost ceramic membranes, peat water, biomass, activated carbon, empty fruit bunches.

INTRODUCTION

Particularly in tropical regions with peatland habitats, like Indonesia and Malaysia, the access to safe drinking water remains a problem worldwide. Elevated amounts of color, acidity, dissolved organic matter mostly composed of fulvic and humic substances as well as high manganese and iron concentrations (Qadafi et al., 2023). These properties complicate conventional treatment techniques and increase the possibility of hazardous by-products during chlorination (Wang et al., 2021). Many rural and semi-urban peatland areas have old-style water treatment systems that do not work well and cost too much. This makes it even more important that new, cheap, and creative ways to treat water and regionally appropriate strategies be found (Rowan et al., 2022).

Ceramic membranes have become a practical alternative to polymeric membranes due to their greater chemical resistance, mechanical strength, thermal stability, and long lifespan (Arumugham et al., 2021). They have shown effectiveness in treating water that has a lot of turbidity and organic materials, providing a steady flow and durability against harsh cleaning methods (Gruskevica and Mezule, 2021). However, the high cost of manufacturing traditional materials, such as high-purity alumina, zirconia, and titania limits the widespread use of ceramic membranes (Fooladi et al., 2024).

Research has increasingly concentrated on LCCMs (low cost ceramic membranes) made from naturally abundant or waste-derived raw materials like clays, fly ash, and silica in order to address these restrictions biomass leftovers and sand (El maguana et al., 2024). By valorizing agricultural waste streams, such methods encourage circular economy principles, in addition to lowering manufacturing costs (Artun and AŞKIN, 2022).

The silica, alumina, and mineral oxides in rice husk, bamboo, coconut shell, and oil palm waste (shells and empty fruit bunches) may act as both. Dele-Afolabi et al. (2022) discussed the structural phases and pore-forming substances involved in membrane production. These materials have been demonstrated to produce membranes with competitive water permeability, adjustable porosity, and waste disposal cost reductions, all while promoting sustainable material cycles and sufficient mechanical stability (Aditama et al., 2024). Additionally, it has been demonstrated that pairing inexpensive ceramic membranes with pre-treatment techniques like coagulation, adsorption, or oxidation can greatly lessen fouling when treating organic-rich waters, delivering synergistic gains in performance (Xie et al., 2025).

Even with these improvements, there are still a few gaps. The feasibility of LCCMs made from clays and industrial by-products has been demonstrated in numerous studies, but systematic investigation into biomass-derived ceramics specifically designed to the distinct chemical composition of peat water is restricted. Because of its combination of low pH, high humic content, and high metal concentrations, peat water is a difficult issue that few studies have addressed directly. First, under such circumstances, ceramic the performance of membranes was connected to the composition of the biomass precursor (Taha et al., 2024). Second, despite research on the integration of ceramic membranes with traditional pretreatment methods for surface and wastewater, there are still very few field-relevant demonstrations for peat water, especially in relation to operational stability, cleaning methods, and long-term fouling behavior (Hakami et al., 2020). Third, the lack of a comprehensive assessment of the sustainability advantages of biomass-derived ceramic membranes restricts the policies and adoption routes in peatland communities. which include savings in embodied energy, cost per cubic meter of water treated, and contributions to circular economy frameworks.

By creating and analyzing affordable ceramic membranes made from locally available biomass waste materials like rice husk and bamboo, this work attempted to bridge these research gaps. The empty fruit bunches, palm shells, and coconut shells are utilized in peat water treatment. This study offers a systematic link between the chemical makeup of biomass precursors and the resulting crystalline phases, microstructure, porosity, and thermal stability of the membranes. understanding the link between structure, characteristics, and performance, which is essential for use in complex water matrices. In an effort to establish a complete framework, the research also examined the use of these membranes in environmentally friendly peat water treatment trains, considered the benefits of the circular economy, material worth, and higher water quality. This research provided a sustainable route "from biomass to clean water," with major implications for decentralized water supply in peatland areas.

MATERIAL AND METHODS

Materials

Local biomass waste residues, such as clay, iron powder, rice husks, bamboos, palm shells, coconut shells, and oil palm empty fruit bunches from which activated carbon is derived. The main raw material for producing ceramic membranes came from empty fruit bunches from oil palms. Deionized water, HCl, and $ZnCl_2$ are just a few of the chemicals utilized in the activation and washing procedures. HCl, ZnCl2 are produced by Merck. Biomass was collected from a village near Palembang City. Activated carbon is produced by Aquazon Model GAC 933, Filter 5 mm and 1 mm, produced by Dewater. For carbonization, a homemade reactor equipped with a heater with adjustable temperature was used. For drying, a self-designed device with adjustable temperature is used. This dryer is made of stainless steel and equipped with an electric heater.

Membrane fabrication

For two hours, biomass leftovers like rice husks, bamboos, palm shells, coconut shells, and oil palm empty fruit clusters were collected, cleaned, sun-dried, and carbonized at 600 °C. Following acid washing with HCl and rinsing with deionized water, the carbonized material was chemically activated using 50% $ZnCl_2$. After being dried for two hours at 400 °C, the substance was pulverized for twenty-four hours in a planetary ball mill. $ZnCl_2$ was used as an activator to remove the impurities contained in pores, so that the pores of the material become empty and the surface area becomes larger. Carbonization at 600 °C was performed to obtain better (purer) carbon. Drying at 400 °C produced drier material with minimal water content.

At a weight ratio of 82.5:15:2.5, the produced activated carbon was crushed and combined with clay and iron powder. Iron powder was used to strengthen the membrane so that it is not easily damaged when subjected to load or pressure. The mixture was cast into tubular molds (5 cm inner diameter, 7 cm outer diameter, 25 cm length) after being homogenized with water to make a paste. The low-cost ceramic membranes (LCCMs) were made by sintering at 900 °C and drying at ambient temperature.

Membrane Characterization

The membranes were analyzed to understand their physical and chemical characteristics. The microstructure and shape were investigated using scanning electron microscopy (SEM) combined with energy-dispersive spectroscopy (EDS) to analyze elemental makeup. The identification of crystalline phases was performed through X-ray diffraction (XRD) within the 2θ range of 10°–80°. The evaluation of thermal stability was conducted using thermogravimetric analysis (TGA). The equipment used to measure TGA was INFITEK TGA-1150, and for SEM – HITACHI SEM SU3500.

Peat water sampling and characterization

Samples of peat water were taken from natural peatlands in Senda Mukti Village, Pulau Rimau District, Banyuasin Regency, South Sumatera Province, Indonesia. The samples were tested for physicochemical parameters such as pH, TDS, TSS, TOC, color, turbidity, Fe, Mn, COD, and BOD before treatment.

Filtration, adsorption and ozonation

Figure 1 shows a series of experimental equipment consisting of coagulation, flocculation, sedimentation, sand filtration, sponge filtration, carbon active adsorption, LCCM membrane separation and ozonation processes.

A pilot-scale filtration system that was set up to work in crossflow mode and tuned to the proper flow rates and operating pressures. The first thing to do to pre-treat peat water was to pour it into

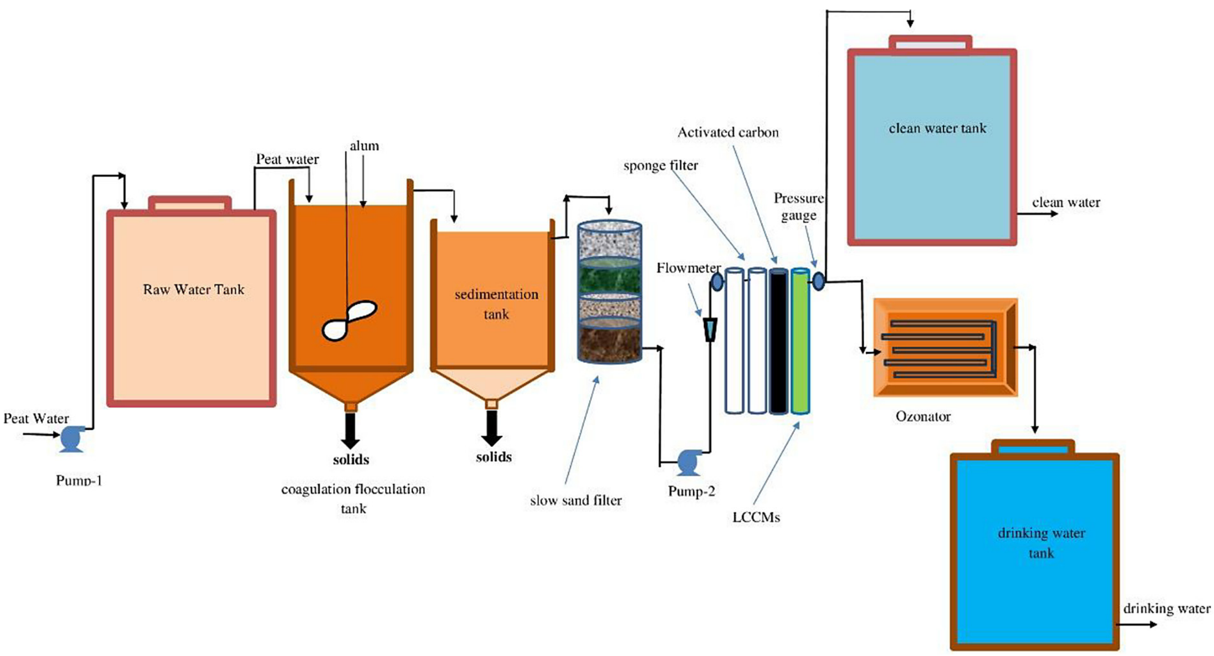

Figure 1. Flow diagram of peat water treatment using LCCMs to produce clean water

a collecting tank. The collecting tank (raw water tank) was used to store raw water to ensure its availability for the peat water purification process. The raw water from Senda Mukti village, Banyuasin, South Sumatera, is pumped into the raw water tank. After that, the water went to a tank for coagulation and flocculation, and then to a tank for sedimentation to separate the solids that have dissolved. After that, it went through an acrylic slow sand filter that includes fine sand, small, medium, and large gravel in it. Then, the water went through sponge filters (0.5 μm and 0.1 μm) and an activated carbon filter in that order Afterwards, the pre-treated water was filtered through the ceramic membranes that had been constructed, with the pressure kept at 2.0 bar. A pressure of 2.0 bar was used, because it was optimal for the equipment used. Higher pressures tend to cause turbulence, while lower pressures can result in very slow fluid flow due to significant system resistance, potentially leading to flow cessation. This 2 bar pressure was applied based on previous research (Sisnayati et al., 2019, Sisnayati et al., 2023). Samples of permeate were collected every 15 minutes for a total of 90 minutes. The prepared LCCMs were used to filter peat water and then examined how effectively the system performed by evaluating the initial flux, how well it removed impurities including color, turbidity, TOC, and metal ions, and how stable the pressure was while it was running. After that, the water was ready to be used as clean water, and two streams are made: one for drinking water and one for clean water. The drinking water stream first runs through an ozonator tank with walls that keep the water in contact with the disinfectant longer, which eliminates all germs, viruses, and bacteria.

RESULT AND DISCUSSION

Membrane characterization

Morphological characteristics from SEM analysis

Five ceramic membranes made from different biomass precursors (A: rice husk, B: bamboo, C: palm shell, D: coconut shell, and E: empty fruit bunch/EFB) show different surface morphologies and pore architectures in scanning electron microscopy (SEM) pictures (Figure 2) and the pore size distributions quantitatively analyzed (Table 1).

Membrane A (rice husk) had a mean pore diameter 0.32 μm and rare macropores. Its pore were consistently between ultrapore (<0.1 μm) and micropore (<10 μm) sizes. The membrane structure is more compact, making it more selective (Njuhou et al., 2023). Membrane B (bamboo) and C (palm shell) had a wider range of pore sizes, with some of them being as big as 15.3 μm and 39.7 μm. Even though it had better flow properties, it did not work. Overall, pore distribution makes it easier for fluids to flow through, it could also make rejection less effective and harm the structure (Zare et al., 2023). In membranes, selectivity is more due to pore size, but because the membrane also contains activated carbon, pollutants can also be adsorbed. Membrane derived coconut shell (D), had a balanced with small pores,

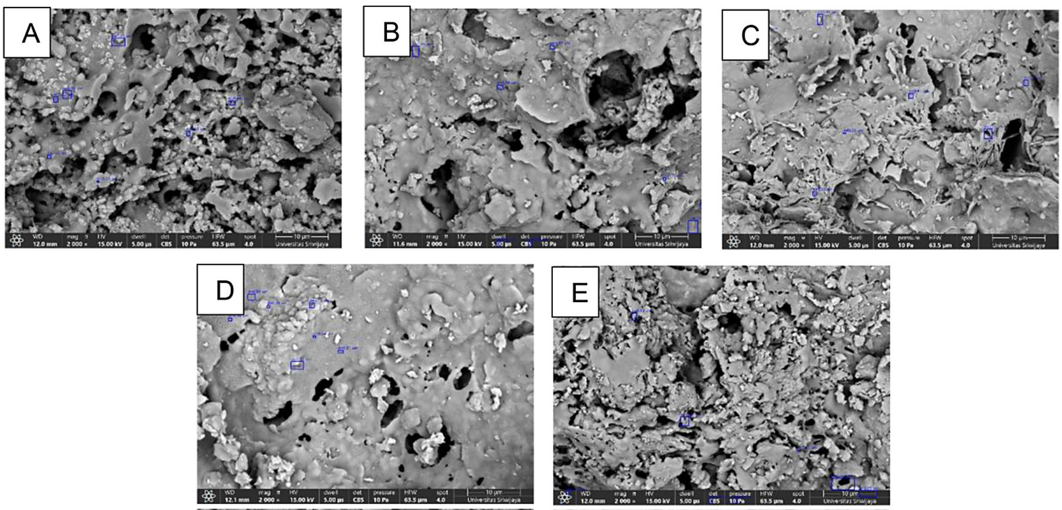

Figure 2. Micrographs of ceramic membranes from different biomass precursors: (A) rice husk, (B) bamboo, (C) palm shell, (D) coconut shell, and (E) EFB

Table 1. Pore size distribution statistics and porosity of ceramic membranes derived from different biomass precursors

Sample	Mean diameter (µm)	Min-max diameter Range (µm)	Porosity (%)	Dominant Regim
A (rice husk)	0.32	0.08–9.6	47.97	Submicron-Micron (rare macropores)
B (bamboo)	0.87	0.11–15.3	50.56	Submicron-Micron (moderate macropores)
C (palm shell)	1.45	0.13–39.7	51.84	Submicron-Micron (frequent macropores)
D (coconut shell)	0.56	0.09–11.2	52.65	Submicron-Micron (elongated pores)
E (EFB)	0.41	0.10–6.8	48.81	Submicron-Micron (rounded micro-voids)

but still had macro-sized pores). This could make the material stronger and let it flow in different directions (Aditama et al., 2024). Membrane E (EFB) showed a stable microstructure with size that were all less than 10 µm. This means the structure is stable and the rejection performance has improved (Sisnayati et al., 2023).

From the SEM analysis results, it can be seen that the pore structure of LCCMs is random and non-uniform, which will directly affect the performance of the filtration process. From Table 1, membranes A (rice husk) and E (EFB) have a narrow pore distribution so that they are expected to provide a high level of selectivity and are suitable for application in microfiltration and ultrafiltration processes (Sisnayati et al., 2019). Membrane C (palm shell) has a broad pore spectrum and offers high permeability but a low level of selectivity (Zhang et al., 2023). Membrane B (bamboo) has moderate macropore characteristics, where the permeability and selectivity are lower than membrane C (palm shell) (Zaini et al., 2025). Membrane D (coconut shell) provides anisotropic transport properties caused by its elongated pores (Yulianto et al., 2024).

Overall, these results emphasize the fundamental trade-off between flux and selectivity governed by pore size distribution, highlighting the potential of biomass precursor selection to optimize membrane performance for certain water treatment contexts.

Porosity analysis

Table 1 shows that the highest to lowest membrane porosities are, respectively: membrane D (coconut shell) 52.65%, membrane C (palm shell) 51.84%, membrane B (bamboo) 50.56%, membrane E (EFB) 48.81%, and membrane A (rice husk) 47.97%. All membranes produce a highly porous network. This is in line with the nature of ceramic membranes derived from silica-rich biomass, which produce a pore network due to volatile combustion (Priyanka et al., 2024), while raw materials rich in carbon/lignin encourage densification and reduce pore volume (Yulianto et al., 2024). Functionally, membranes C and D support higher flux values but may still require selective surface coatings to remove fine contaminants (Njuhou et al., 2023). Low porosity membranes (C, D) are good as support layers because they are more mechanically stable (Taha et al., 2024). Membranes A (rice husk) and E (EFB) are also good as support layers, because they are more mechanically stable (Pradhan et al., 2024).

Energy dispersive x-ray spectroscopy (EDS) analysis

The EDS analysis results presented in Figure 3 show that ceramic membranes produced from biomass are primarily composed of oxygen (O), silicon (Si), aluminium (Al), and carbon (C).

The differences in the elemental composition of these ceramic membranes reflect the mineralogical characteristics of the precursor biomass and are important in determining the sintering treatment, crystallization stage, and functional properties of the membrane (de Oliveira et al., 2025). The composition of the ceramic membrane materials is shown in Figure 4.

In membrane A (rice husk), the EDS spectrum shows a dominant contribution from oxygen (50.6 at.%) and silica-related elements (Si: 12.9 at.%), along with significant Fe (9.6 at.%) and Al (6.8 at.%). This high silica content aligns with the known chemical properties of rice husk ash, which is rich in amorphous SiO_2. This composition provides excellent thermal stability and chemical resistance, while the presence of Fe can

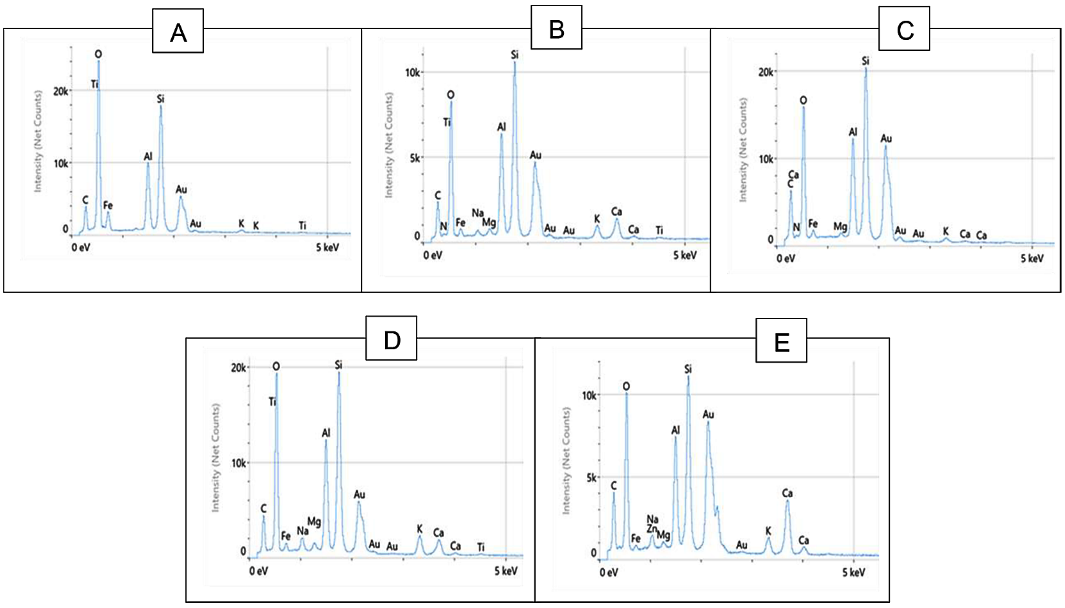

Figure 3. EDS spectra of ceramic membrane derived from rice husk (A), bamboo (B), palm shell (C), coconut shell (D), and empty fruit bunch (E)

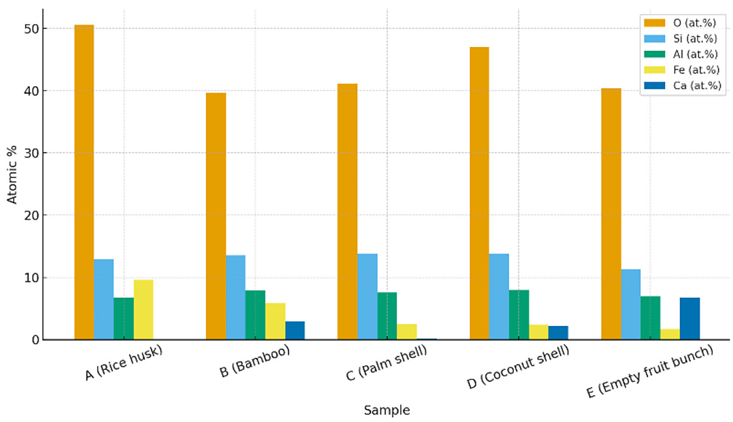

Figure 4. EDS composition of biomass-derived ceramic membrane

act as a fluxing agent to aid sintering and introduce redox-active sites (Loy et al., 2020). These findings are consistent with a report by Njuhou et al. (2023), which showed that silica-rich raw materials improve refractoriness and selectivity in ceramic membranes.

The bamboo-derived membrane (B) exhibits 13.6% Si, 7.9% Al, and moderate contributions from Ca (2.9% Si) and Fe (5.9% Si), with oxygen contributing 39.6% Si. This more balanced composition indicates the development of mullite ($Al_6Si_2O_{13}$) and calcium silicate phases during sintering, which contribute to mechanical strengthening and densification (Ibrahim et al., 2023). Such chemistry explains the denser microstructure often reported for bamboo-derived ceramics (Zaini et al., 2025).

The membrane derived from palm kernel shells (C) contains 13.8% Si, 7.6% Al, and high carbon (23.2%), with trace amounts of Fe (2.5%) and Ca. This suggests the presence of a silica-alumina framework with embedded carbon and Fe oxide residues. The relatively high Fe content, although lower than that of rice husks, may still promote catalytic activity, while the residual carbon contributes to pore formation during firing (Jalaluddin et al., 2023). These results align with recent the findings that palm oil residues produce heterogeneous ceramics with bimodal pore structures and redox functions (Malebadi et al., 2025). The coconut shell membrane (D) exhibited the Si content of 13.8% and the Al content of 8.0%, along with higher levels of alkali/alkaline earth metals (Na: 1.6%, K: 2.3%, Ca: 2.2%), and moderate Fe (2.4%). This composition suggests the formation of calcium silicate and alkali-bearing phases during sintering, which promote densification but also risk microcracking due to mismatched thermal expansion (Sun et al., 2022). Similar effects of the Ca-rich compositions on structural anisotropy and shrinkage behavior have been reported for coconut shell ceramics (Aripin et al., 2022).

Finally, the coconut shell membrane (E) exhibited a multiphase composition with 11.3% Si, 7.0% Al, significant Ca (6.8%), and trace Zn (1.0%). The detection of Zn, although minor, is important as it can contribute to surface charge modification and antimicrobial activity, thus enhancing multifunctionality. The combination of silica, alumina, and calcium demonstrated the coexistence of mullite and calcium silicate, with the Zn phase potentially enhancing catalytic properties (Lima et al., 2022). This is in line with the findings of Malebadi et al., (2025) that the EFB-derived ceramics exhibit a variety of functionalities suitable for water purification.

Overall, the EDS results indicate that silica-rich precursors (rice husk, bamboo) produce stable and selective membranes, while Ca-rich and alkali precursors (coconut shell, EFB) promote higher densification and porosity, and precursors containing Fe or Zn (palm shell, EFB) offer catalytic or multifunctional potential. These insights indicate that precursor mineralogy plays a crucial role in tailoring the performance of ceramic membranes for water treatment applications, especially in challenging feedwater conditions such as peat water (El Azizi et al., 2023).

X-ray diffraction (XRD) analysis

X-ray diffraction (XRD) patterns of ceramic membranes synthesized from various biomass precursors are presented in Figure 5. The results indicate the presence of crystalline and amorphous phases, characteristic of silica–alumina-based ceramics, with variations arising from differences in the composition of each raw material, as shown in Table 2.

Figure 5 shows that the membrane derived from rice husk (Figure 5A) exhibits sharp diffraction peaks at $2\theta \approx 22°$ and 26°, corresponding to the (101) and (200) planes of cristobalite/silica quartz. The presence of broad background scattering indicates the presence of a partially amorphous silica phase, which is consistent with the high silica content in the rice husk ash. Minor peaks associated with mullite ($Al_6Si_2O_{13}$) are also detected, reflecting the contribution of alumina during sintering. The dominance of the silica-rich crystalline phase is in line with previous studies highlighting the excellent thermal stability and chemical resistance of ceramics derived from rice husk (Islam et al., 2025). The bamboo-based ceramic membrane (Figure 5B) exhibits crystalline reflections corresponding to quartz (SiO_2) and mullite, with strong peaks near $2\theta \approx$ 21–26°. The relative intensity of mullite reflections is higher compared to rice husk, indicating enhanced alumino-silicate interactions during sintering. This suggests that bamboo, despite its lower initial silica content, promotes mullite crystallization due to its balanced silica-alumina ratio (Zhang et al., 2022). The palm shell-based membranes exhibit quartz diffraction peaks with slight hematite (Fe_2O_3) reflections, consistent with the moderate iron oxide content identified in EDS. A broad halo is also observed, indicating the presence of residual amorphous carbonaceous material after calcination. The quartz-hematite composite structure contributes to thermal stability and catalytic activity. Similar crystalline features have been reported in palm shell ash-based ceramics, where Fe oxides are incorporated into the silico-alumina framework (Yang et al., 2024). The coconut shell-derived membrane exhibits distinct peaks for SiO_2 and secondary calcium silicate (Ca_2SiO_4) phases around $2\theta \approx$ 29–32°, which arise due to its relatively high Ca content. This crystal feature indicates flux-assisted crystallization during sintering, which can lead to the development of a strong but crack-prone microstructure. The coexistence of quartz and calcium silicate phases has also been reported in coconut shell-based ceramics, where flux oxides influence porosity and mechanical stability (Kaou et al., 2025). The EFB-derived membrane exhibits a more heterogeneous diffraction pattern, with reflections from quartz, mullite, and traces of calcium silicate and zinc oxide (ZnO). The detection of Zn-related peaks aligns with trace elements identified by EDS, indicating the incorporation of micronutrient metals into the crystal structure. The broader background scattering indicates a partially amorphous phase, typical of biomass-derived ceramics with mixed inorganic compositions. This multiphase structure can provide multifunctionality, combining mechanical strength, thermal stability, and potential catalytic activity (Sawunyama et al., 2024).

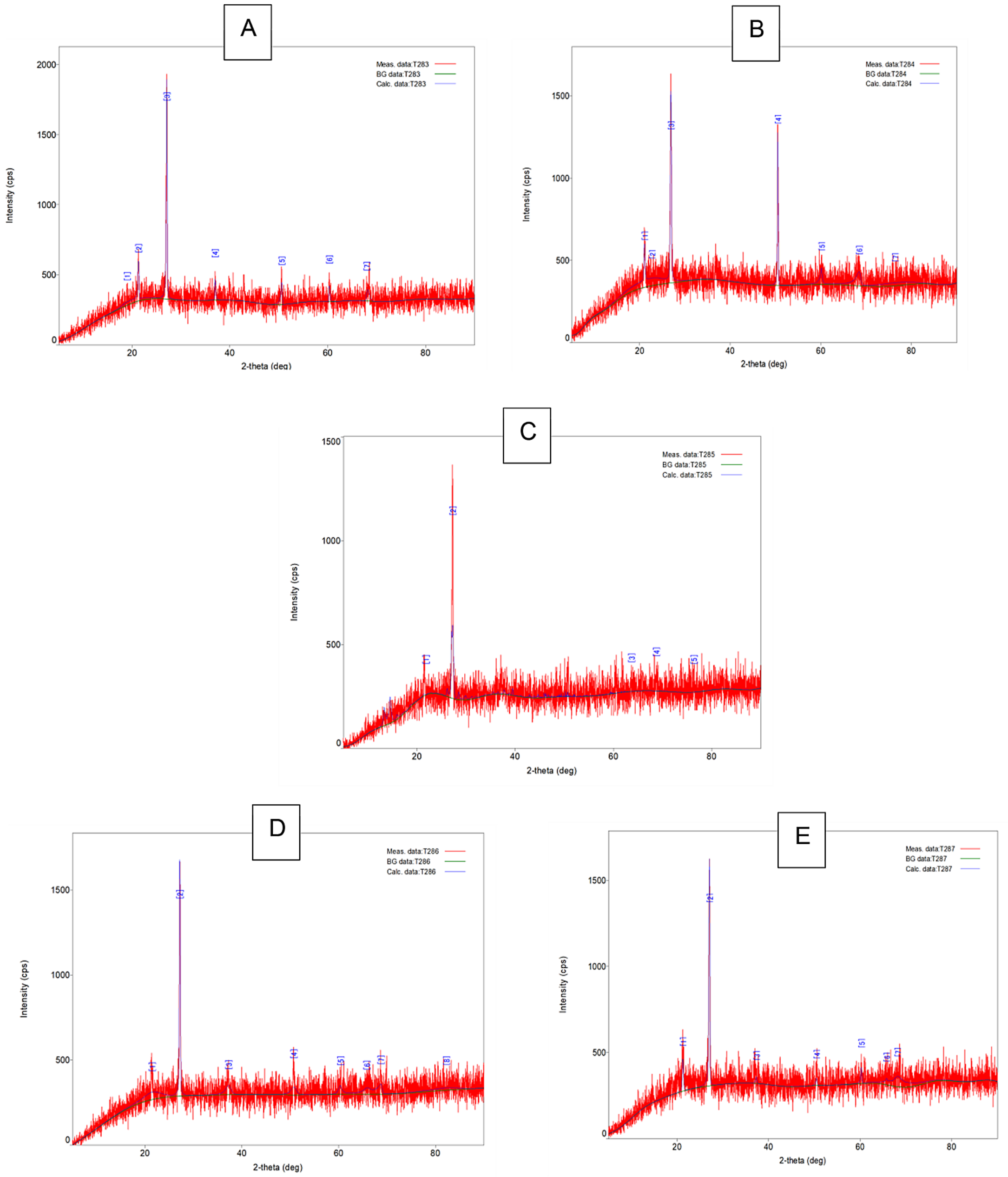

Figure 5. X-ray diffraction (XRD) patterns of ceramic membranes derived from (A) rice husk, (B) bamboo, (C) palm shell, (D) coconut shell, and (E) empty fruit bunch

Overall, all ceramic membranes exhibited SiO_2 as the dominant crystalline phase, complemented by secondary phases, such as mullite (Al–Si–O), hematite (Fe_2O_3), and calcium silicate, depending on the precursor composition. These results indicate that the choice of biomass precursor significantly determines the evolution of the crystalline phase, which in turn controls the functional properties of the membrane. This is consistent with the recent reports highlighting the role of precursor mineralogy in determining the crystalline-amorphous balance of ceramic membranes (Abdullayev et al., 2019).

TGA analysis

Figures 6 and 7 show the residual mass resulting from the thermogravimetric analysis (TGA) of ceramic membranes at certain temperatures and times for various types of ceramic membrane forming materials, namely rice husks (A), bamboo (B), palm shells (C), coconut shells (D), and EFB (E). Thus, the performance of one material can be compared with other materials contained in the ceramic membran

TGA was performed to evaluate the thermal stability and decomposition profiles of ceramic

Table 2. Summary of X-ray diffraction (XRD) results of ceramic membranes prepared from different biomass precursors

Sample	Dominant phase (s)	Main 2 theta Peaks (°)	Implications
(A) rice husk	Quartz (SiO_2), Cristobalite, Amorphous SiO_2	22°, 26°	High silica, good thermal and chemical stability
(B) bamboo	Quartz (SiO_2), Mullite ($Al_6Si_2O_{13}$)	21–26°, 40–45°	Mullite enhances densification and strength
(C) palm shell	Quartz (SiO_2), Hematite (Fe_2O_3)	26°, 33°	Fe oxides improve catalytic and thermal behavior
(D) coconut shell	Quartz (SiO_2), Calcium silicate (Ca_2SiO_4)	26°, 29–32°	Ca silicates increase toughness but risk microcracks
(E) empty fruit bunch	Quartz (SiO_2), Mullite, Calcium silicate, ZnO	26°, 29–32°, 36–38°	Multiphase: versatile, with potential ion-exchange/catalysis

membranes derived from various biomass precursors, namely rice husks (A), bamboo (B), palm shells (C), coconut shells (D), and EFB (E). The TGA results showed distinctive thermal behavior, reflecting differences in the intrinsic composition of the raw materials, particularly regarding silica, lignocellulosic components, and residual inorganic phases.

TGA was conducted to evaluate the thermal stability and breakdown characteristics of ceramic membranes produced from several biomass precursors, namely rice husk, bamboo, coconut shell, palm shell, and EFB. The TGA curves demonstrated unique weight loss trends for each precursor, with the EFB-derived membranes showing the least weight loss, signifying enhanced thermal stability relative to other biomass-derived membranes. This indicates that EFB, owing to its elevated carbon content and mineral composition, facilitates the development of more robust ceramic structures during sintering, evidenced by the little weight loss above 600 °C. The membranes obtained from rice husk and bamboo exhibited marginally greater weight losses owing to the decomposition of remaining organic constituents at lower temperatures (300–400 °C), which correlates with the combustion of volatile organic compounds and the volatilization of carbonaceous materials (Feng et al., 2021).

Rice husk (A) had a residual mass of 95.9% at 700 °C, while bamboo (B) had a residual mass of 98.81%. Palm shell (C) had a residual mass of 99.19%, and coconut shell (D) and empty fruit bunch (E) had residual masses of 95.62% and 96.82%, respectively. Thus, palm shell had the largest residual mass. This can also be seen in Figure 7.

The TGA results also showed that the thermal degradation profiles of each precursor were very different from each other. The membranes derived from palm shell and coconut shell showed significant weight reduction within the temperature range of 400–600 °C, attributable to the volatile constituents inherent in these materials, including lignin and cellulose. These results align with the findings of Yulianto et al. (2024), which indicated that high-carbon, lignin-rich feedstocks such as palm shell and coconut shell enhance porosity and membrane flexibility, while also leading to greater weight loss during sintering (Yulianto et al., 2024). The higher thermal degradation of these feedstocks indicates that their membranes may possess increased porosity and diminished mechanical strength relative to those fabricated from EFB or rice husk (Bat-Amgalan et al., 2024).

The TGA study of the EFB-derived membranes exhibited a distinct degradation pattern characterized by steady weight loss, culminating in a stable plateau beyond 600 °C. This response signifies little organic content and implies that the membranes exhibit thermal stability at elevated operational temperatures. This stability is essential for sustained performance in high-temperature filtering applications, particularly in industrial water treatment. The reduced weight loss noted in EFB-based membranes supports the premise that the EFB-derived ceramics possess superior thermal stability and durability, rendering them suitable for sustainable, cost-effective filtration methods in complex water matrices such as peat water (Samadi et al., 2022).

Membrane performance

The characterization investigation of biomass-derived ceramic membranes indicates that the membrane produced from oil palm empty fruit bunches (E) demonstrated the most advantageous features. Consequently, this study further assessed its efficacy in converting peat water into clean and potable water (Table 3).

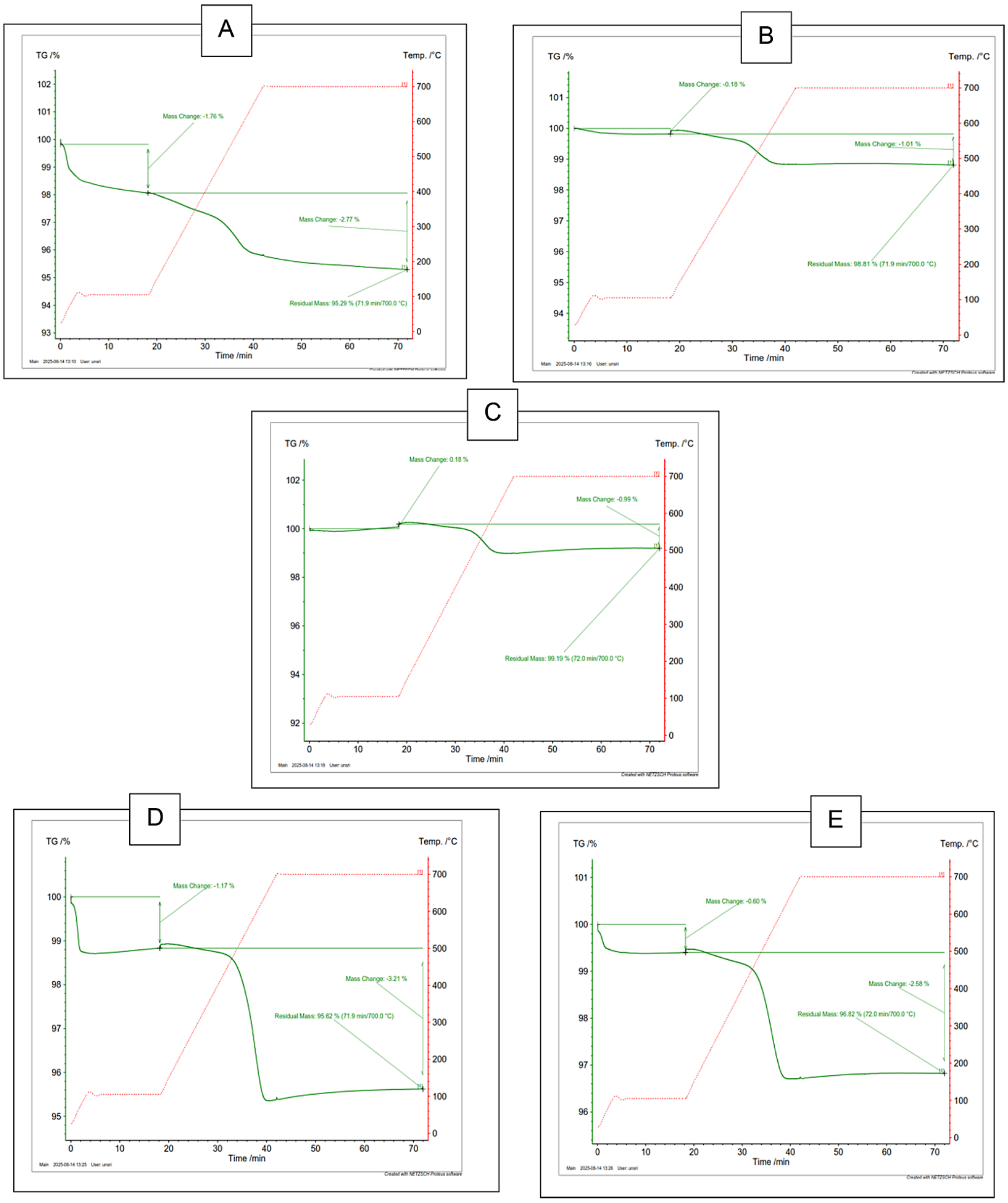

Figure 6. Thermogram of ceramic membranes derived from (A) rice husk, (B) bamboo, (C) palm shell, (D) coconut shell, and (E) empty fruit bunch

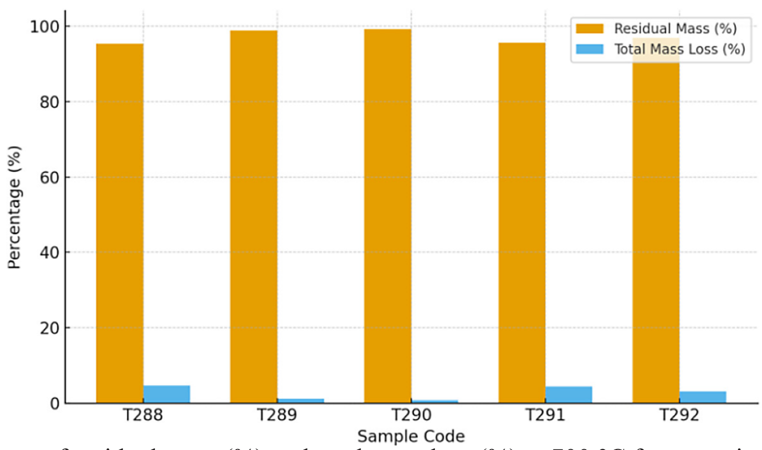

Figure 7. Comparison of residual mass (%) and total mass loss (%) at 700 °C for ceramic membranes derived from rice husk (T288), bamboo (T289), palm shell (T290), coconut shell (T291), and empty fruit bunch (T292)

Table 3. Water quality of raw peat water, clean water, and drinking water using EFB-derived ceramic membranes compared with regulatory standards

NO	Parameter	Unit	Standard limit*	Raw peat water	Clean water	Drinking water
Physical						
1	Odor	#	Odorless	Odorous	Odorless	Odorless
2	TDS	mg/L	<300	**549**	170.1	27.9
3	Turbidity	NTU	<3	**8.52**	2.65	1.50
4	Temperature	°C	Ambient ± 3	30.2	30.5	30.7
5	Color	TCU	10	**64.8**	8.3	5.3
Chemical						
6	Cadmium (Cd)	mg/L	0.003	**-**	-	0
7	Manganese (Mn)	mg/L	0.1	**0.69**	0.02	0.01
8	Iron (Fe)	mg/L	0.2	**6.01**	0.1	0.05
9	Nitrite (NO_2)	mg/L	3	1.17	<0.001	<0.001
10	pH	#	6.5 - 8.5	**4.41**	6.93	7.2
11	Free Chlorine (Cl_2)	mg/L	0.2–0.5	**-**	-	0.01
12	Lead (Pb)	mg/L	0.01	**-**	-	0
13	Flouride (F)	mg/L	1.5	**-**	-	0.27
Microbiological						
11	*E Coli*	CFU/100 ml	0	**8.7**	0	0
12	*Coliform*	CFU/100 ml	0	**14.5**	0	0

Note: *The standard values are based on Permenkes RI No. 2 Year 2023 Environmental Health Quality Standards for Hygiene and Sanitation Purposes

The raw peat water used in this study had high levels of dissolved solids (TDS 549 mg/L), turbidity (8.52 NTU), color (64.8 TCU), acidity (pH 4.41), iron (6.01 mg/L), manganese (0.69 mg/L), and microbial contamination (*E. coli* 8.7 CFU/100 mL; *coliform* 14.5 CFU/100 mL), which are typical problems of tropical peatland resources. These features align with earlier studies showing that humic compounds, dissolved organic debris, and transition metals predominate in peat water, all of which make traditional treatment procedures more difficult and provide health hazards, if left untreated (Jarrar et al., 2024).

Significant gains were seen after pretreatment and EFB-based ceramic membrane filtration, resulting in water that satisfied clean water standards. Microbial counts were lowered to zero, and significant decreases were observed in TDS to 170.1 mg/L (69.0%), turbidity to 2.65 NTU (68.9%), color to 8.3 TCU (87.2%), Fe to 0.10 mg/L (98.3%), and Mn to 0.02 mg/L (97.1%). The pH rose to 6.93, which is within the neutral range that is safe to eat. These outcomes are consistent with new research on ceramic membranes made from biomass, which shows remarkable results in lowering turbidity, metal ions, and microbial loads while preserving mechanical and chemical stability (Kanth et al., 2025).

With TDS down to 27.9 mg/L (94.9% total reduction), turbidity to 1.50 NTU (82.4%), and color to 5.3 TCU (91.8%), along with Fe (0.05 mg/L) and Mn (0.01 mg/L) far below allowable limits, additional polishing improved the quality even further to satisfy drinking water requirements. The safety of the treated water was validated by its final pH of 7.2, lack of odor, and removal of microbiological contamination. Crucially, using ceramic membranes made from EFB not only guarantees adherence to national and WHO requirements but also serves as an example of the circular economy strategy by turning agricultural waste into useful components for decentralized water treatment systems in peatland areas (Nouira et al., 2025).

CONCLUSIONS

In order to treat peat water – difficult feedwater source with high levels of organic matter, dissolved metals, acidity, and microbial contamination – this study shows how to successfully fabricate and apply inexpensive ceramic membranes made from oil palm empty fruit bunches (EFB). The precursor mineralogy of EFB promotes the formation of porous, thermally stable, and chemically resistant ceramic structures appropriate for water purification applications, according to thorough characterization (SEM, EDS, XRD, and TGA).

Filtration trials demonstrated that the EFB-based ceramic membrane efficiently transformed raw peat water into clean water and subsequently into potable water that complies with both national and WHO requirements. Significant enhancements comprised reductions above 90% in turbidity, color, and organic load, with over 98% elimination of Fe, Mn, and microbiological pollutants, in addition to pH adjustment to neutral levels. These findings underscore the significant potential of biomass-derived ceramics to concurrently attain elevated pollutant rejection, mechanical strength, and operational stability.

The findings affirm that EFB-based ceramic membranes provide a sustainable and scalable option for decentralized water provision in peatland areas, while enhancing circular economy advantages through the valorization of agricultural waste. This study integrated waste-to-resource pathways with advanced water treatment, offering a novel addition to inexpensive, environmentally sustainable, and resilient solutions for ensuring access to clean and safe drinking water in vulnerable populations.

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