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Review article

Application of coal fly ash based ceramic membranes in wastewater treatment: A sustainable alternative to commercial materials

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ABSTRACT

The continued increase in the global population has resulted in increased water demand for domestic, agricultural, and industrial purposes. These activities have led to the generation of high volumes of wastewater, which has an impact on water quality. Consequently, more practical solutions are needed to improve the current wastewater treatment systems. The use of improved ceramic membranes for wastewater treatment holds significant prospects for advancement in water treatment and sanitation. Hence, different studies have employed ceramic membranes in wastewater treatment and the search for low-cost and environmentally friendly starting materials has continued to engender research interests. This review focuses on the application of coal fly ash in membrane technology for wastewater treatment. The processes of membrane fabrication and the various limitations of the material. Several factors that influence the properties and performance of coal fly ash ceramic membranes in wastewater treatment are also presented. Some possible solutions to the limitations are also proposed, while cost analysis of coal fly ash-based membranes is explored to evaluate its potential for large-scale applications.

1. Introduction

The incessant rise in the world's population has resulted in higher water requirements for household, farming, and industrial needs. Consequently, the quality of water is affected due to the substantial generation of wastewater. However, this wastewater can be harnessed and repurposed for various applications [1–3]. Wastewater management is crucial for sustainable development [4]. According to a study by Obaideen et al. [5], wastewater treatment helps to successfully achieve 11 out of the 17 Sustainable Development Goals. Contaminants found in wastewater include pathogens, pesticides, dyes, heavy metals, pharmaceuticals, surfactants etc [6].

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These contaminates significantly affect both animal and human health as well as aquatic ecosystems even at low concentration levels. Significant efforts have been made to overcome the challenges of wastewater in recent years and these include policy and implementation as well as the development of treatment techniques [7,8]. These techniques are classified as either conventional methods or advanced treatment methods. Advanced treatment methods include constructed wetlands, bioelectrical systems, membrane filtration technologies, adsorption, advanced oxidation processes such as Fenton oxidation processes, photocatalysis, electrochemical oxidation, and enzymatic treatment [9–11]. Conventional methods include coagulation-flocculation and ozonation. However, due to financial and technological constraints, only a limited number of the numerous and diverse treatment techniques mentioned for wastewater treatment are utilized for domestic and economic purposes [12]. To tackle the unresolved problems of global water scarcity and water pollution, there is a need for water treatment solutions that possess multiple functions, can be scaled up, are strong and reliable, do not rely on chemicals, have a minimal environmental impact, and are energy-efficient [13]. Inadequate wastewater treatment methods have led to the recent discovery of a new class of pollutants called emerging contaminants in the environment, which have not yet been completely eradicated from the ecosystem [14]. As a result, more research is needed to enhance the current wastewater treatment systems so that it complies with the established regulations to totally remove pollutants.

The use of membrane technology in wastewater treatment has drawn attention from all around the world because it uses few chemicals, effectively removes contaminants, environmentally friendly, energy-efficient, and simple [15–17]. Membranes serve as selective barriers that permit some elements pass through while keeping others [15,18]. The utilization of membranes in wastewater treatment relies on the fundamental concept of allowing water molecules to pass through selectively while trapping contaminants, achieved by applying a driving force across the membrane. Membranes are primarily categorized into organic (polymeric) and inorganic (ceramic) types [16]. Organic membranes are those that are made up of nonporous polymeric materials, such as cellulose acetate, polyethersulfone, polyimide, polysulfone, polymethylpentene, polycarbonate, polydimethylsiloxane, and polyphenylene oxide [19,20]. Ceramic membranes are fine artificial porous membranes made from sintering inorganic materials, such as alumina, zirconia oxide, titanium, silicon oxide, silicon carbide, and silicon nitride or a combination of these materials under high temperatures [21,22]. At the moment, large-scale polymeric membrane systems are widely used over inorganic membranes due to good selectivity, ease of controlling pore size during formation, high flexibility, and cost-effectiveness [23]. Most applications of polymeric membranes are in gas separation and desalination due to high permeation and selectivity. They are, however, under-utilized in areas such as wastewater treatment due to low stability towards high temperatures, chemicals and harsh conditions [24]. Consequently, inorganic membranes have rapidly received global attention in being considered as one of the potential candidates to replace available polymeric membranes [25] due to several characteristics such as high stability under a variety of operating conditions such as temperature, and toxic chemicals, high eco-compatibility and scalability [26]. This review will focus exclusively on inorganic ceramic membranes.

Ceramic membranes can be classified as either symmetric or asymmetric based on their structural properties (Fig. 1) [27]. Symmetrical structured ceramic membranes have pores that are uniform in size across the membrane's thickness as shown in Fig. 1a. Conversely, asymmetric ceramic membranes feature three layers with pore patterns that are greatest on one surface and smallest near the other surface Fig. 1b [28,29]. The membrane relies on a macroporous support that offers robustness due to its larger pores. Additionally, an intermediate layer with smaller pores compared to the support layer safeguards against material intrusion during fabrication. Lastly, the selective active layer, featuring even smaller pores than the intermediate layer, effectively rejects pollutants

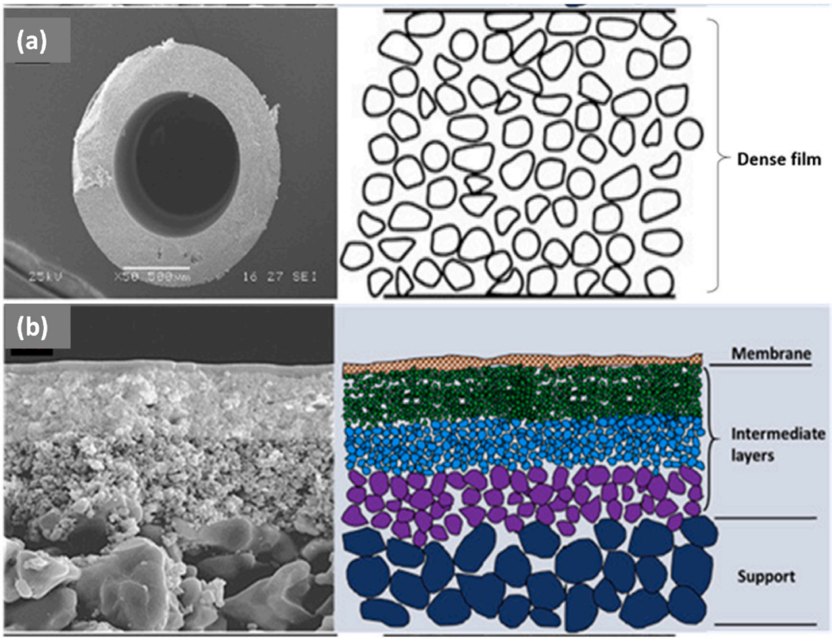

Fig. 1. The typical cross-section of (a) symmetrical ceramic membrane [35] and (b) an asymmetrical ceramic membrane [36].

[30]. Ceramic membranes are categorized into microfiltration (MF), ultrafiltration (UF), and nanofiltration (NF) based on the size of their pores. The pore sizes for each category are the ones that are greater than 50 nm, the one that ranges from 2 to 50 nm, and less than 2 nm, respectively [31].

The utilization of ceramic membrane technology in wastewater treatment is experiencing a rapid expansion owing to its extended durability, chemical stability, and minimal fouling inclination [32]. They also have excellent thermal stability which makes them useable in high-temperature operations [33]. Ceramic membranes can successfully eliminate various pollutants from wastewater through processes such as size exclusion, adsorption, and electrostatic repulsion. The efficiency of separating pollutants in wastewater using ceramic membranes depends on factors such as the membrane's pore volume, pore size, size distribution, and surface chemistry [34].

Application of ceramic membranes is mainly at the laboratory scale due to the high cost of raw materials, multi-manufacturing steps and high sintering temperatures [37,38]. The estimated cost price of ceramic membranes ranges from $500 to $1000 per square meter, with the price of polymeric membranes accounting for 25 % of that price [33]. In order to enhance the price competitiveness of ceramic membranes for large-scale applications, it is imperative to lower the fabrication costs associated with them [39]. The use of improved ceramic membranes for wastewater treatment appears to hold a significant prospect for future advancement in water treatment and sanitation. Several studies have employed ceramic membranes in wastewater treatment and the search for low-cost and environmentally friendly starting materials has continued to engender research interests. Therefore, solid wastes and readily available materials rich in Al_2O_3 and SiO_2 such as coal fly ash, natural clay, kaolin and sand can be used as starting material for ceramic membranes [40–43]. Studies by Hossain and Roy [44] and Sawunyama et al. [45] reported that coal fly ash and bentonite clay had significant amounts of Al_2O_3 and SiO_2 which can make them good candidates for ceramic membranes raw materials. It has been demonstrated in numerous studies that it is possible to fabricate ceramic membranes from coal fly ash. Recently, Rao et al. [46] fabricated a novel fly ash blended/potter clay ceramic membrane. Fu et al. [47] also prepared a low-cost ceramic membrane from coal fly ash as the main raw material and AlF_3 as the catalyst. SiC ceramic membrane with mullite bonds were also fabricated from coal fly ash, silicon carbide and 5 % MoO_3 [48]. The utilization of these affordable starting materials in large-scale membrane processes presents sustainability, environmental benefits and potential high removal efficiencies for pollutants [30,49,50]. In addition to resolving the problem of poor water quality, the use of coal fly ash in ceramic membranes in wastewater treatment represents a milestone in waste management because coal fly ash has detrimental environmental consequences [51].

According to a Scopus analysis of publications (spanning over a 20-year period) on coal fly ash-based ceramic membranes, about 175 research papers have been published, with the highest publication occurring in 2023 (Fig. 2). This is a sign of a lately popular study area that is beginning to receive significant attention from researchers. Few review articles have examined the different functional roles that coal fly ash plays in the fabrication of ceramic membranes for wastewater treatment. This review, therefore, provides up-to-date information on the use of coal fly ash as sustainable raw material for the fabrication of ceramic membrane. Finally, the causes and management of fouling in coal fly ash-based ceramic membranes are discussed, as well as the fabrication cost and future prospects. This review will contribute to the expansion of understanding on the application of coal fly ash in the fabrication of ceramic membranes.

2. Coal fly ash

Coal fly ash is a residue that is generated through the combustion of pulverized coal in thermal power plants [52]. It is an extremely fine, heterogeneous powder mixture of crystalline and amorphous phases with spherical geometry, and particle sizes between 10 and

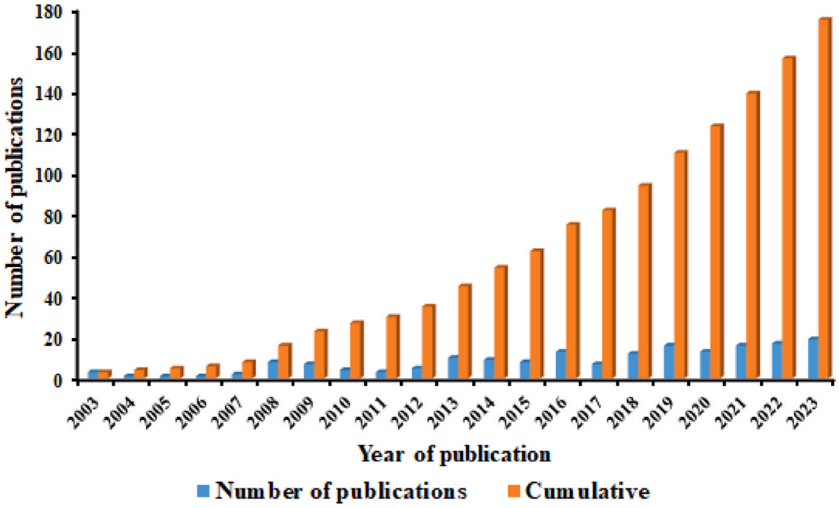

Fig. 2. Analysis of publications from Scopus database on coal fly ash based ceramic membranes over the past 20 years (search was performed using the keywords "coal fly ash + ceramic membrane).

100 μm [53,54]. Oxides of silicon, aluminium, calcium, iron, and calcium are the main components of coal fly ash. There are also little amounts of magnesium, calcium, potassium, sodium, titanium, and sulphur as shown in Fig. 3. Significant levels of hazardous metals such As, Ba, Hg, Cr, Ni, V, Pb, Zn, and Se are also present in the coal fly ash [55,56]. These toxic substances may seep out of it and pollute the environment. Additionally, they may cause cancer, skin and lung infections, nausea, vomiting, and organ dysfunction in people [57].

Chemical composition, mineralogy, and coal source are used to categorize coal fly ash. The combined mass composition of silicon dioxide, aluminium dioxide, potassium oxide, titanium dioxide, and phosphorus oxide is used to classify coal fly ash in terms of its chemical composition [58,59]. Calsialic, ferrisialic, ferricalsialic, and sialic are the various classes. Based on mineralogy, coal fly ash can also be classified as magnetic spinel and mullite-quartzite [60]. Coal fly ash can be further divided into two classes: Class C and Class F, depending on where the coal came from. Class F is from bituminous and anthracite coals, which have a lower calcium concentration than Class C's high calcium content (above 20 %) lignite and sub-bituminous coals [61–63]. Compared to Class C, Class F contains a higher percentage of alumina, silica, and iron (around 70 %) [64]. High calcium content in class C results in the production of a greater amount of calcium-aluminate-silicate hydrate, whereas Class F's higher silicon content produces a greater amount of sodium-aluminate-silicate-hydrate [60,65,66]. The source of the coal, the amount of ash in the coal, the degree of coal mining and preparation, the conditions during combustion and mining, the current climate, and other pertinent aspects all affect the properties (physical and chemical) and composition of coal fly ash [67].

Around 8025 Mt of coal were used worldwide in 2022 (Fig. 2a) by several industries, including cement manufacturing, iron and steel production, and power generation. As a result, a lot of coal fly ash is being produced, but less than 30 % of them are being recycled. Consequently, disposal takes up a lot of space, which is a significant problem. Transporting the coal fly ash for disposal also comes at a considerable expense. Coal fly ash is also harmful to the environment since it can contaminate the air, water, and soil and leach hazardous compounds [69–71]. Because of this, experts are now concerned about how to properly manage, dispose of, and use coal fly ash. Even though there has been a lot of research done on the global usage of coal fly ash (Fig 4a), the building industry as shown in Fig 4b is currently where it is most frequently used. These applications are ascribed to shape, surface area, high strength, lightweight, and non-toxic and porosity, among other physical characteristics [72]. The most lucrative application of coal fly ash in terms of volume is as a raw material for ceramic membranes, yet little study has been done in this field.

3. Synthesis of coal fly ash based ceramic membranes

The fundamental components required for the manufacture of ceramic membranes include inorganic precursors, and additives such as solvents, dispersants, pore formers, binders, and plasticizers. The fabrication process involves three primary steps which are: (1) preparation of suspension or paste from precursor material and additives, (2) shaping the suspension/paste into a desired geometry such as tubular, plate or disc configuration and (3) drying, and sintering of the resultant ceramic membrane [75]. An optional step, which involves the leaching of undesired elements in the coal fly ash before the mixing of raw materials and additives is determined by the analysis of the elemental composition of the coal fly ash. The allowable concentrations of these elements are guided by the thresholds indicated in the national guidelines for heavy metal release. This is due to the possible presence of large levels of toxic metals such as Ba, As, Hg, Cr, Ni, V, Pb, Zn, and Se in coal fly ash [76,77]. The most common manufacturing techniques for ceramic

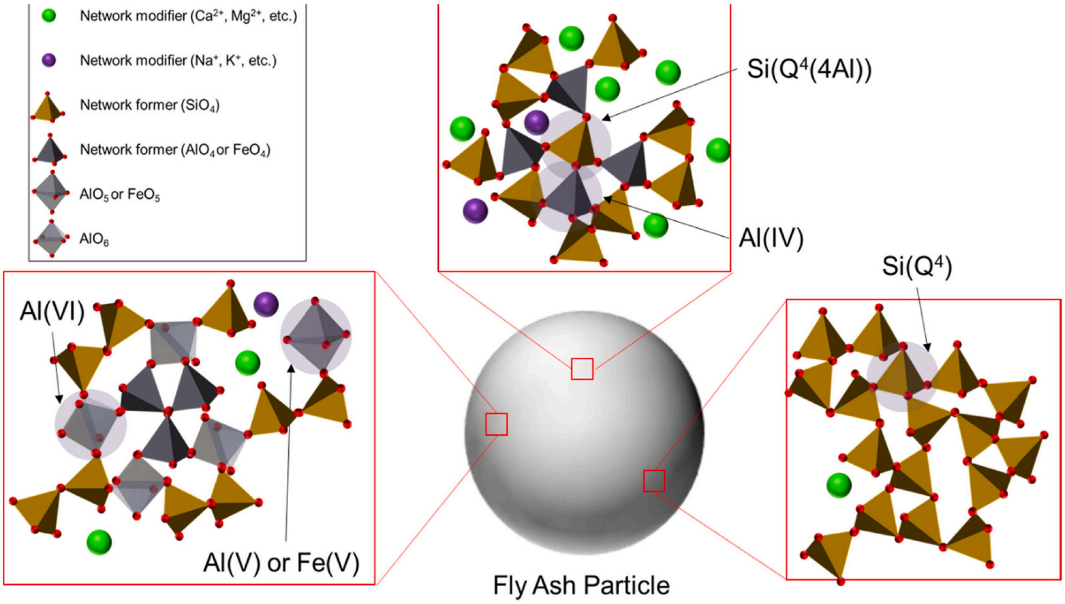

Fig. 3. Schematic Illustration of the structure of coal fly ash [68].

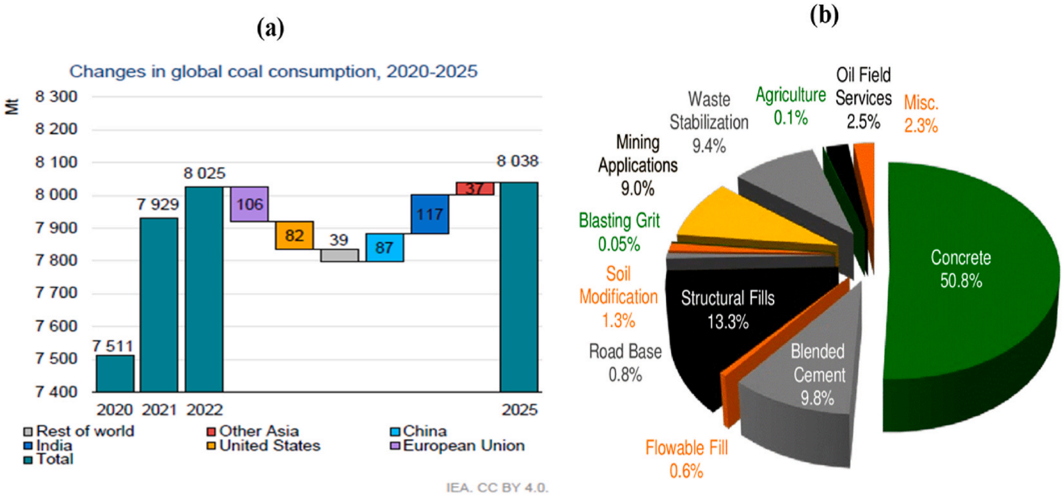

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Fig. 4. (a) Changes in global coal consumption (b) various uses of coal fly ash [73,74].

membranes are freeze casting, slip casting, tape casting, pressing and extrusion. The choice of a ceramic membrane fabrication technique depends on application requirements, the desired membrane geometry, and the specific starting materials [78]. In the fabrication of ceramic membranes, the additives have a variety of important functions. The viscosity of the slurry is controlled using solvents like water and those with organic bases, such as acetone, to make it easier to spread over the carrier film and to increase the uniformity of the additives in the ceramic powder. Ceramic particles can be held together using binders such as polyvinyl alcohol [79–81], sodium metasilicate [82,83], carboxymethyl cellulose (CMC) [84], and others. The settling of the powder particles is prevented by the use of dispersants like sodium hexametaphosphate [34], sodium carbonate, and boric acid [82]. In order to make synthetic membranes more flexible, glycerine is mostly utilized as a plasticizer. The porous ceramic membrane's porosity is increased using pore-forming materials including dextrin [84,85], calcium carbonate [81,82,86], and spherical graphite [79,87] which decompose completely during the sintering process. Table 1 gives the properties, configurations, and fabrication techniques of some coal fly ash based ceramic membranes.

3.1. Synthesis of coal fly ash ceramic membranes by pressing method

Axial pressing and isostatic pressing are the two pressing techniques used in the fabrication of ceramic membrane supports. Axial pressing is classified as dry or wet, with dry pressing involving dry powders without water and wet pressing involving the addition of water to ceramic raw materials. The two types of isostatic pressing are cold pressing and hot pressing. Cold isostatic pressing creates membrane support using external pressure, but hot isostatic pressing creates the desired shape using heating. While isostatic pressing applies pressure from various directions to boost shape capabilities, axial pressing is more affordable and appropriate for high volume manufacture of simple geometrical ceramic membranes [88]. Apriyanti et al. [89] used the dry pressing method to fabricate flat ceramic membrane from coal fly ash. When a pressure of 1 bar and calcination temperature of 1100 °C for 7 h was applied, the resulting membrane was more durable and had a homogeneous surface free of any cracks. The coal ash membrane's major crystal structure morphology was Al_2O_3, according to XRD analysis. Due to the formation of a robust and porous ceramic membrane, the findings from the study demonstrated that coal fly ash can be used as a raw material for ceramic membranes. Liu et al. [90] fabricated a cylindrical-shaped porous ceramic membrane using wet ball milling and uniaxial pressing. Dolomite was employed as a pore-forming agent, sintering inhibitor, and reactant in addition to coal fly ash as the starting material. The findings demonstrated that the addition of dolomite effectively modified the support pore structure by increasing pores through the release of CO_2 and preventing coal fly ash from sintering while supplying sufficient mechanical strength and good thermal characteristics in the finished porous ceramic membrane. In a similar study, Chathurappan et al. reported the suitability and effectiveness of dry pressing method in the fabrication of coal fly ash based ceramic membranes. The main raw materials used in the synthesis process were coal fly ash and fuller clay. The procedure involved in the fabrication is shown in Fig. 5 [91].

3.2. Synthesis of coal fly ash ceramic membranes by extrusion method

One of the often-employed conventional methods for fabricating multi-channel ceramic membranes that may be produced on an industrial scale is extrusion. The homogeneous, high-viscosity paste created by combining aggregate powder with additives is vacuum melted and aged. The additives form the required plastic properties for effective shape-forming without losing cohesiveness. The uniform high viscosity paste is then extruded into tubular supports by a nozzle after entering the vacuum extruder. To preserve the synthetic membrane's final structure, the remaining chemicals are evaporated. The most significant factors for process control are the applied pressure in extrusion and the rate of extrusion. The diameter of the raw material, the amount of binder, and the sintering

Table 1
Techniques used in the manufacturing of coal fly ash-based ceramics and the properties of the resulting membranes.

Ceramic membrane	Fabrication method	Additives	Characteristic of the synthesized material	Ref.
Hydrophobic Coal-Fly-Ash-Based Ceramic Membrane	Extrusion	sodium hexametaphosphate of the suspension served as a dispersant and the PVA acted as a binder	Increased pore size from 0.15 μm to 1.57 μm, the water flux rose	[34]
Highly porous whisker-structured mullite ceramic membranes	Uniaxial pressing	MoO_3 as a single sintering additive Organic binder polyvinyl alcohol	Open porosity showed a significant increase from 41.65 ± 0.13 % to 58.14 ± 0.15 % as the MoO3 content increased from 0 to 20 wt%, accompanied by a decrease in shrinkage and pore size in the absence of any pore-forming agent	[103]
Coal fly ash based multipurpose ultrafiltration membrane	Uniaxial pressing	–	The membrane porosity-39.8 % hydraulic pore radius - 41 nm. The membrane pure water flux increased from 2.09 to 11.31 m^3/m^2 sec as the applied pressure increased from 69 to 483 kPa.	[91]
Low-cost microfiltration membranes from fly ash	Paste-casting	Sodium carbonate and boric acid act as dispersant Sodium metasilicate acts as binder Calcium carbonate act as pore forming agent	The membranes, which were defect-free, possessed an average pore size ranging from 1.2 to 2.3 μm and displayed excellent chemical stability in both acidic and basic solutions. Furthermore, they had a porosity level of 35–40 %.	[82].
Porous mullite ceramic supports from high alumina fly ash	Dry pressing method	Spherical graphite as pore-forming agent. Polyvinyl alcohol (PVA) as a binder	Whose apparent porosity 55.7 %, Flexural strength 8.5 MPa and	[87]
Kaolin-fly ash-based membranes	Paste-casting method	H_3BO_3 and na_2co_3 were used to provide homogeneity Calcium carbonate defines the pore morphology Sodium metasilicate ($na_2sio_3.9h_2o$) acts as a binder.	Porosity (~34.36–39.0 %), pore size (~0.65–1.81 μm) flexural strength (~10–30 mpa)	[83]
SiC-Coal fly ash ceramic membranes	dry pressing method	Polyvinyl alcohol Graphite- pore former	Porosity 54.46 % exhibited good, mechanical properties	[79]
Coal fly ash ceramic membrane	extrusion method	Dolomite used as a pore-forming Carboxymethyl cellulose (cmc) used as a binder Glycerin used as a plasticizer,	Large particles reduced mechanical strength of fly ash based membranes while increasing porosity.	[104]
Lumina based tubular asymmetric membranes incorporated with coal fly ash	Centrifugalcasting technique	–	Increased porosity and enhanced water permeability coincide with reduced mechanical strength and diminished linear shrinkage	[105]
High-aluminum coal fly ash ceramic membrane supports	Uniaxial cold-pressing	PVA solution as organic binder $CaCO_3$ pore forming agent	Mechanical strengths 34–90 MPa	[86]
Coal fly ash-based tubular ceramic membrane	Extrusion	Dextrin as pore-forming agent CMC, as organic binder Glycerin, to improve the plasticity	Porosity 38.9−45.9 % Mechanical strength 14.8−36.0 MPa	[84]
Fly ash cenosphere ceramic membrane	uniaxial pressing	organic binder PVA- $CaCO_3$- pore forming agent	Porosity 59.25 % Mechanical strength 70 ± 2.58 MPa	[81]
Tubular supported ceramic microfiltration membranes from fly ash	Slip- casting	Dispersant lomar-d Binder dsx 3290	Average pore diameter 0.77 μm. Pure water permeability- 1.56×10^4 L m^{-2} h^{-1} bar^{-1}, respectively, Transmembrane- 0.1 MPa at room temperature.	[97]
Mullite-whisker-structured porous ceramic membrane	Uniaxial pressing	Binder- PVA-1750 AlF_3 as crystallization catalyst MoO_3 as mineralizer	A porosity of 45.4 ± 0.9 % was obtained.	[106]
Fly ash ceramic membrane	Slip casting method	Polyvinyl alcohol	Pore size- 1.47 (μm Porosity- 39 (%) Mechanical strength 1.98 (MPa)	[107]
Tubular coal fly ash based ceramic membranes.	Extrusion method	Dextrin as pore-forming agent CMC, as organic binder Glycerin, to improve the plasticity	Porosity- 44.76–47.30 % Mechanical strength 15.16–29.11 (MPa)	[85]

temperature on the support affect the qualities and performance of the synthesized membrane [92,93]. Huang et al. synthesized coal fly ash based ceramic membrane with high efficiency for water and heat recovery. Dextrin was utilized as a binder, while carboxymethyl cellulose was used as a pore-forming agent. The procedure involved in the fabrication is shown in Fig. 6 [85]. In another study, Jedidi et al. [94] reported the fabrication of porous tubular coal fly ash based ceramic membrane using extrusion method. At a constant sintering temperature of 1125 °C, it was demonstrated that the ceramic membrane synthesized exhibited favourable mechanical and chemical resistances. Additionally, it possessed a significant average porosity of 51 % and a mean pore diameter of 4.5 μm. The membrane's permeability was measured at 475 L h^{-1} m^{-2} bar.

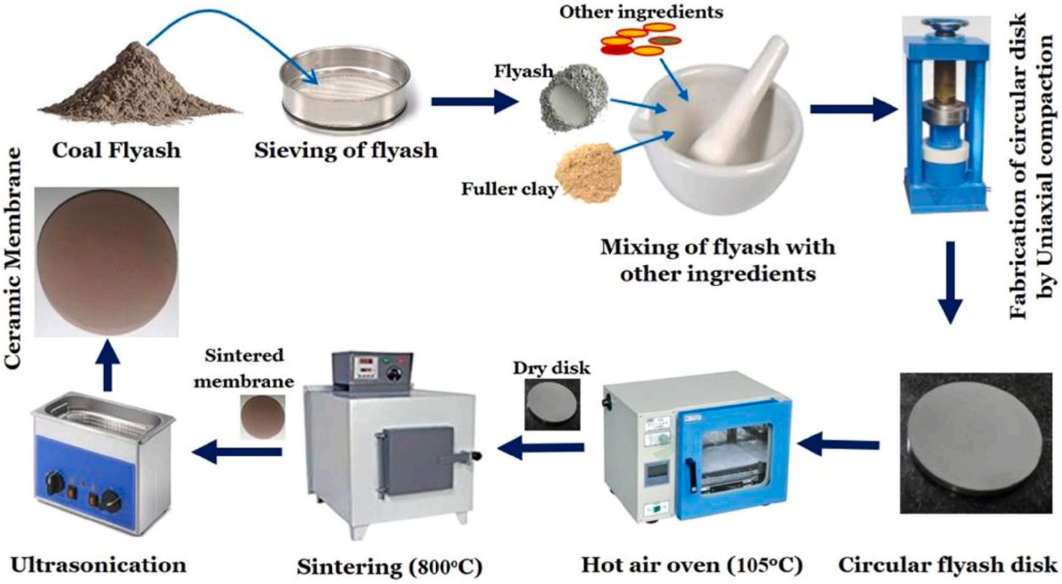


Fig. 5. Schematic illustration for the preparation of coal fly ash based ceramic fabrication by dry pressing method [91].

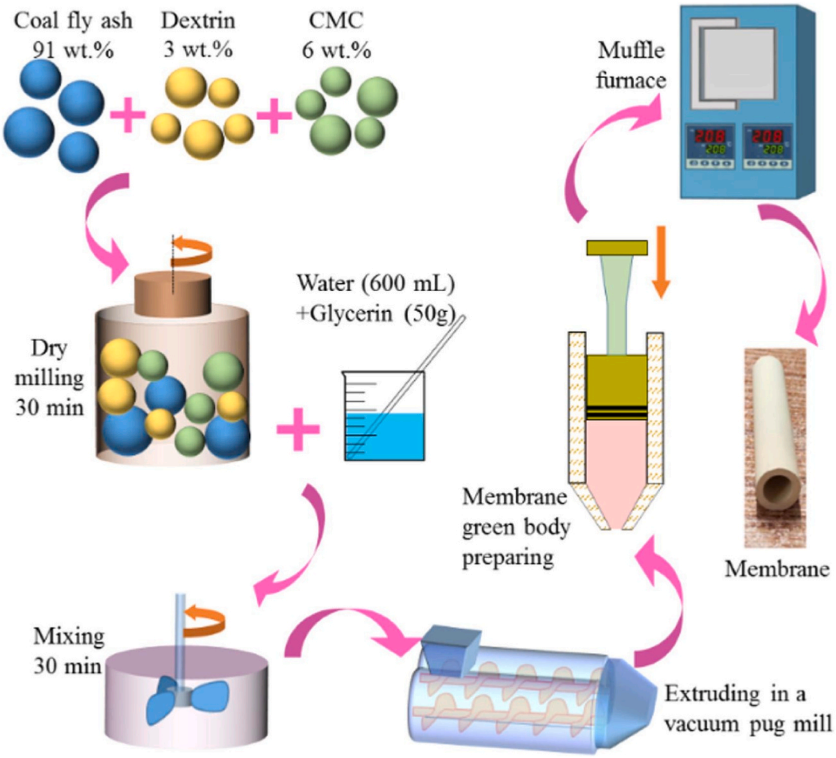


Fig. 6. Fabrication of coal fly ash based ceramic membrane via extrusion method [85].

3.3. *Synthesis of coal fly ash ceramic membranes by slip casting method*

Slip casting is an easy, affordable, and adaptable technique. It is used to fabricate ceramic membranes with complicated shapes that are non-concentric and uneven. In slip casting technique high solid content suspensions are poured into porous cast molds, allowing the solvents to seep through the pores and precipitate the particles into a layer as illustrated in Fig. 7. The resultant material is sintered after de-moulding, which is the final step in producing the desired ceramic membrane. The fabrication of ceramic membranes from coal fly ash using the slip casting method was first reported by Jedidi et al [95]. The primary chemical components of the coal fly ash employed in the study are mainly comprised of SiO_2, Al_2O_3, and Fe_2O_3. The minor components were made up of a variety of alkali metals. Fly ash powder, distilled water, and polyvinyl alcohol (PVA) were mixed to create the slurry. The final membrane was subjected to a thermal process that involves 24 h of room temperature drying followed by 800 °C sintering. SEM images showed that the membrane surface was uniform and free of cracks. The results showed that the active layer's average pore diameter was 0.25 μm and its thickness was close to 20 μm. The fabricated ceramic membrane had a 475 L/h m^2 bar permeability. A number of factors, such as sintering temperature, casting time, suspension pH, particle size, etc., have an impact on the properties of slip casted ceramic membranes [96]. Fang et al. [97] investigated the effect of slip concentration, withdrawal speed and casting time on the preparation of coal fly ash ceramic membrane fabricated using the slip casting technique. The findings showed that an increase in slip concentration causes a significant increase in membrane thickness as well as an increase in porosity because more particles adhere to one another. Additionally, it was reported that the optimum slip concentration should be utilized to prevent the development of surface flaws like cracks. The average pore size distribution and pore diameters were observed to be unaffected by casting time and pull-out speed, while the thickness of the membrane was found to be affected.

3.4. Synthesis of coal fly ash ceramic membranes by tape casting method

Thin, flat dense ceramic membranes made of ceramic slurry are fabricated using tape casting technique. The steps in the tape casting method are as follows: A slurry made of inorganic powder and additives such as binders, dispersants, and plasticizers are continually dispensed onto a moving substrate while a doctor blade could be adjusting the thickness (Fig. 8). Then, the cast film is dried and sintered to form the resultant ceramic membrane. The benefit of tape casting is that ceramic sheets can be configured into any desired shapes, including circular, square, and rectangular shapes and also allows adjustment of the thickness of the ceramic membrane [99]. However, the main problem with tape casting is the loss of shape accuracy caused by the deterioration of the plaster mould. Tape casting also takes a very long time when a slurry of small granules is cast [100]. Several factors, including the viscosity of the slip, the distance between the knife blade and the moving carrier, the depth of the reservoir, and the speed of the carrier, can affect the tape casting process used to fabricate the ceramic membranes [101].

4. Application of coal fly ash in ceramic membrane for wastewater treatment

The increasing demand for environmental protection and the reuse of waste materials, implies that the utilization of CFA in different aspects of membrane development is being continually sought. The presence of heavy metals such as chromium, vanadium and antimony in CFA is a factor that has limited its application due to the possibility of long-term leaching. This has necessitated the pre-treatment of the CFA prior to its use in ceramic membranes. Nugteren et al. [108] reported a forced leaching process using water, citrate, EDTA, oxalate and carbonate solutions. The use of cation exchange membrane assisted electrokinetic method for the removal of heavy metals from CFA has been reported by Peng et al. [109]. After the removal of heavy metals, CFA can serve the following five major purposes in the development of membranes for wastewater treatment.

4.1. Membrane precursor

The large amount of CFA being generated as waste in coal-fired electrical power stations, means it can be a readily available raw material for several industrial processes. Due to its high composition of SiO_2 and Al_2O_3, CFA can serve as an economical precursor for the synthesis of ceramic membranes for wastewater purification.

CFA has been significantly explored as raw material for the synthesis of mullite-based ceramics. Mullite is a solid solution with several unique properties, such as, low thermal conductivity, high chemical resistance and temperature stability, low thermal expansion coefficient and high flexural strength [110,111]. CFA pickling could be an important pre-treatment process in enhancing the

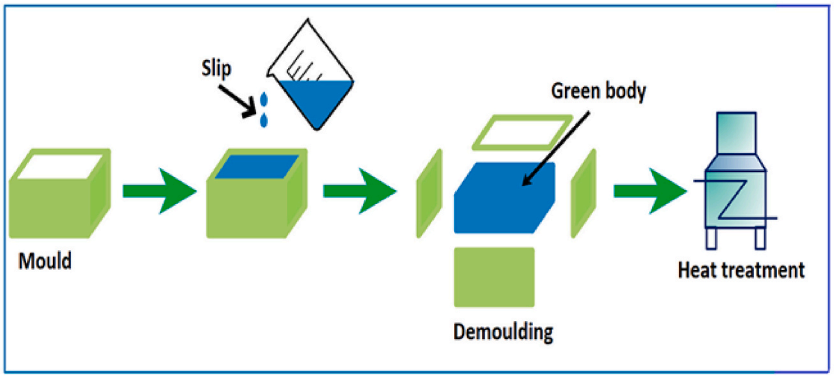


Fig. 7. Schematic illustrations of the slip casting technique for fabricating ceramic membranes [98].

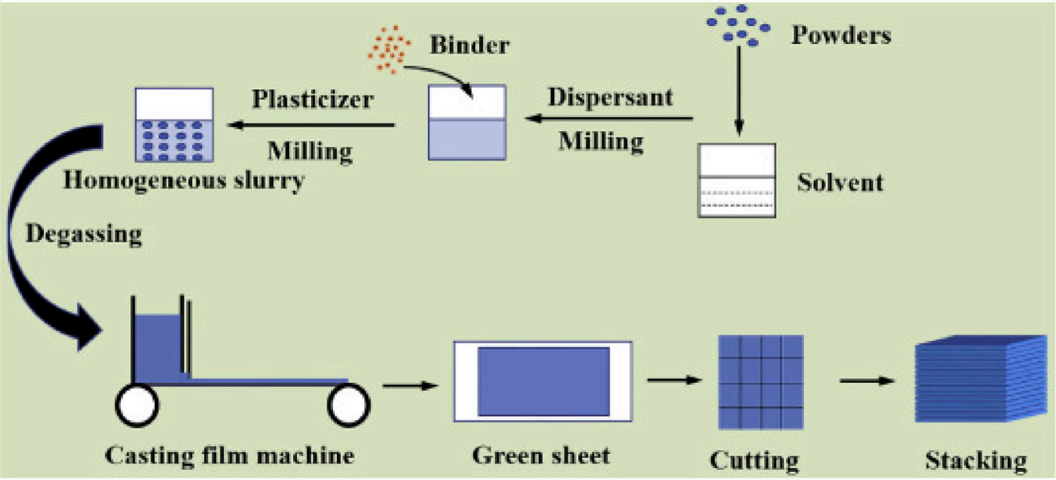


Fig. 8. Schematic illustrations of the tape casting technique for fabricating ceramic membranes [102].

flexural strength of mullite ceramics Li et al. [112]. Also, the sintering temperature and the addition of AlF_3 as a whisker promoter could influence the final property of the obtained ceramic. AlF_3 was observed to influence properties such as phase composition, porosity, bulk density, and aspect ratio of the obtained whiskers. Mullite obtained from CFA was employed together with multiwalled carbon nanotubes (MWCNT) to form a hierarchically structured membrane, the membrane achieved complete retention of *E. coli* and *S. Aureus* [113]. Interestingly, no pore blockage was reported for the material and fouling only occurred due to the bacterial cell deposition of the surface.

Tobermorite, a crystalline calcium silicate hydrate, is another ceramic material that has been obtained using CFA as a raw material [114]. The excellent mechanical properties and durability of tobermorite, makes it a potential material in various structural application. The high reaction activity of tobermorite has been reported to allow for a lower sintering temperature compared to traditional ceramics Luo, Ma [114]. Aluminum substitution and morphology were also observed to be two factors that influenced the mechanical property of the membrane. Tobermorite from waste materials such as newsprint recycling residue and, paper recycling ash have been reported as efficient adsorbent and cation exchanger in a few studies [115–117].

In another study, the synthesis ofAl_2O_3-NaA zeolite hollow fibre membranes from CFA with high efficiency for Pb(II) ions removal in low concentration has been reported Zhu et al. [118] reported. The membrane displayed a pore diameter of 0.41 nm, permeation flux of 670 ± 20.6 $L/h/m^2$ and Pb(II) ion removal reached 99.9 % at 0.1 MPa. The high membrane area per volume and thin thickness of the Al_2O_3 support was important in enhancing the permeation flux of the composite membrane.

4.2. *Sintering additive*

The presence of additives often influences shrinkage, dimensional changes, grain growth and homogenization during sintering of ceramics. With the aid of appropriate additives, the sintering temperature of ceramics can be reduced through the formation of eutectic composition [119,120]. The sintering additive should enhance densification without decomposing the base materials, while also introducing a weak interface. Das et al. [121] reported the use of CFA as sintering additive in the synthesis of a mullite bonded porous SiC ceramic membrane. The obtained membrane exhibited high water flux of 5261 L/m/h bar, mean pore size of 3.7 μm open porosity of 44.4 %. The membrane was able to achieve 91 % removal of oil from a kitchen wastewater with initial oil concentration of 1657 mg/L. The presence of CFA as a sintering additive, allowed for the processing of the membrane at a lower temperature, without comprising its mechanical and permeability characteristics.

4.3. *Membrane filler*

To improve the hydrophilicity and stability of polymeric membranes, inorganic fillers have become very important in forming mixed matrix membranes. These membranes possess numerous advantages arising from the synergy between the organic and inorganic phases [122]. Several studies have explored the incorporation of ceramic metal oxides such as cerium oxide (CeO_2), zirconium dioxide (ZrO_2) and aluminium oxide (Al_2O_3) as nano-fillers for ceramic membranes in wastewater treatment because of their potential to enhance the selectivity, surface area, hydrophilicity and stability of polymeric membranes [123]. Because of the large amounts of fly ash being produced by power stations and the similarity between the chemical composition of fly ash and traditional raw materials, the use of fly ash in membrane fillers as high economic and environmental value [124]. The mechanical properties of ceramics obtained using fly ash fillers, generally depends on the quantity of the reinforcing materials, component of ceramic, porosity, shape, interfacial interaction between filler and composite matrix and the presence of other reinforcements [125]. As observed by Manocha et al. [125], the porosity of a carbon-fly ash-ceramic composite was observed to increase with higher fly ash composition. This improved porosity, however, implies that the membrane suffers from reduced coefficient of friction. This limitation could be mitigated by adding silicon carbide into the mixture, which led to an improvement in the coefficient of friction of the membrane.

The use of CFA-modified ceramics has been explored in various wastewater treatment processes because of their unique advantages. Recently, Rao et al. [46], reported the application of a novel fly ash blended/potter clay ceramic membrane in microbial fuel cell (MFC) technology for COD removal from wastewater. The hydration property of the membrane showed CFA concentration dependency, resulting from the variation in the concentration of SiO_2 and Al_2O_3 in the composite as the quantity of CFA is varied. This is significant for the ceramic membrane's proton conduction efficiency and their optimal composition is highly important for improved membrane performance. The introduction of CFA as fillers for the membrane reportedly improved the thermal stability, optimized the pore size distribution and heterogeneity, enhanced water uptake, improved proton conductivity, and decreased oxygen mass transport coefficient. This improved property of the CFA-modified membranes was important in the wastewater treatment efficiency of the ceramic membrane. CFA-filled ceramic membranes were also reported as micro-electrolysis ceramic media for the pre-treatment of tetracycline wastewater. Two novel ceramics: sintering ferric-carbon (SFC) and sintering-free ferric-carbon ceramics (SFFC) based on coal ash, and scrap iron were used in tetracycline wastewater pre-treatment to improve biodegradability, removal efficiency and inhibit antibiotic-resistant bacteria growth [126].

4.4. Membrane filters

Microfiltration membranes comprising of CFA active layer is another well explored application of CFA in wastewater treatment. Most fly ash membranes developed till date have been focused on the treatment of oily wastewater. However, the numerous advantages of the materials mean it is being explored also in the removal of other organic and inorganic pollutants from water. Recently, CFA-based membranes have been utilized in the treatment of effluents from textile and tin industries, domestic households, and poultry slaughterhouses. Table 2, shows the application of CFA-based membranes in the treatment of different industry generated effluents. CFA-based membranes have also been found to be effective for the removal of bacteria, phenol, and humic acid from wastewater.

The synthesis of microfiltration membranes with CFA as both microporous support and active layer has been reported Jedidi et al. [94]. The active layer obtained by slip-casting and sintering yielded a pore size of 0.25 μm and possess a water permeability of 475 L/h m^2 bar. The membrane showed high efficiency in the treatment of dyeing effluents from the textile industry. The stabilised permeate flux was 100 L/h/m^2, the COD and color removal were 75 and 90 % respectively, with the permeate turbidity reduced to 0.5 NTU from the initial 45.5 NTU.

Modification of CFA membranes with nanostructured materials is a potential route to obtaining highly efficient filters for wastewater treatment. The incorporation of nanoparticles could influence the properties of CFA-membranes such as hydrophilicity, permeation flux, and their adsorption property [132]. Zhang et al. [132] synthesized Fe_3O_4@CFAS with high efficiency for Cu(II) ion removal. The incorporation of Fe_3O_4 resulted in an enhancement of the hydrophilicity of the membrane, with no significant alteration in the permeation flux of the composite membrane observed. The improved hydrophilicity played a significant role in enhancing the adsorption property of the composite as it promotes contact and chelation of active sites with Cu(II) ion.

The use of CFA as membrane support have also reported in literatures. The synthesis of a porous mullite-whisker-structured ceramic membrane supported with CFA and bauxite as starting materials was reported by Zhu et al [106] reported, while AlF_3 and MoO_3 acted as crystallization catalyst and mineralizer, respectively. The introduction of MoO_3 was observed to lead to a reduction of the high temperature viscosity of liquid melts which promoted the growth of elongated mullite crystallites. The open porosity of the membrane was observed to be enhanced by the introduction of AlF_3. At the optimal weight composition of MoO_3 and AlF_3 (5 and 4 wt%

Table 2
Application of CFA-based membranes in the treatment of different effluent.

Description	Fabrication technique	Composition	Membrane characteristic	Wastewater type	Efficiency	Reference
Tubular microfiltration membrane	Extrusion	75 % CFA, 20 % quartz; 5 % calcium carbonate	Pore size: 0.133 μm Porosity: 40.17 %; Water permeability17.75 × 10^5 (Lm^{-2}h^{-1}bar^{-1})	Poultry slaughterhouse wastewater	COD removal: 100 %; TSS: 100 %	[127]
Tubular membrane	Extrusion	75 % CFA, 20 % quartz; 5 % calcium carbonate	Pore size:0.133 μm; Water permeability:4.93 × 10^{14} Lm^{-2}h^{-1}bar^{-1} Tortuosity:1.68	Starch-rich wastewater	COD: 100 % TOC:100 % Turbidity:100 %	[128]
Fly ash/alumina composite membrane	Thermal spraying	Mullite whiskers/fly ash/polyvinyl alcohol/glycerol	Pore size: 0.1 um Permeability: 445 Lm^{-2}h-1bar^{-1}	Oily emulsion and stannic acid rejection	TOC: 99 % Tin rejection: 99.9	[129]
TiO2-fly ash membrane	Hydraulic press and hydrothermal synthesis	Fly ash:80 %; Quartz:10 %: Calcium carbonate:10 %	Porosity:35 % Pore size: 1.32 μm; Permeability: 6.135 Lm^{-2}h^{-1}bar^{-1}	Oil-in-water emulsion	Oil rejection: 98.7 %	[130]
Kaolin/fly ash composite membrane	Sintering	AFA/kaolin/fly ash	Pore diameter: 0.32 μm; Permeability: 3650 Lm^{-2}h^{-1}bar^{-1}	Distillery wastewater	Oil rejection: 98.05 %	[131]

respectively), the open porosity of the membrane was 47.3 ± 0.6 %. The study further affirmed that despite the enhancement of the membrane's porosity, the mechanical strength was not compromised even though the membrane was prepared at a relatively low temperature of 1200 °C. The membrane achieved a total organic carbon removal of over 90 % at 0.2 MPa for oil-in-water emulsion.

Recently, the synthesis of TiO_2 nanofiber membrane loaded on porous fly ash ceramic support was reported by Zhang et al. [133]. The novel composite membrane obtained from fly ash, graphite and industrial rutile was fabricated using a semi-dry press and hydrothermal process. The composite membrane showed excellent activity for the simultaneous removal of heavy metal ions and rhodamine B. The capacity of the membrane for dual functionality as both adsorbent and photocatalyst makes it a potential cost effective material for wastewater treatment.

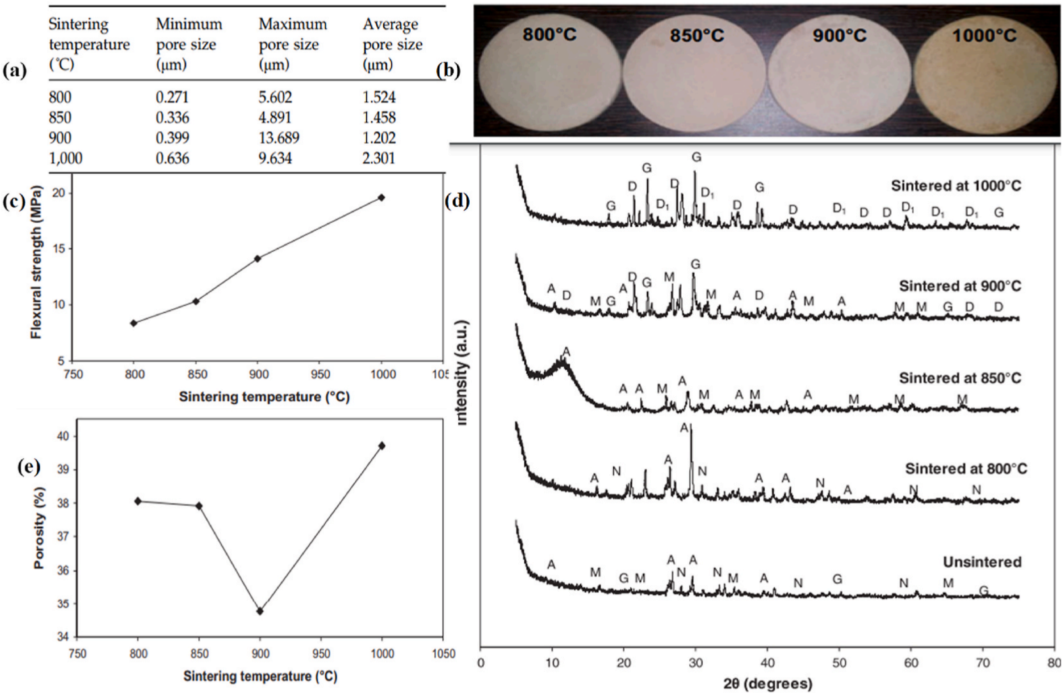
The solute rejection efficiency at a constant flux of a choline chloride blended cellulose acetate membrane, used in CFA support, demonstrated dependence on pH. When the pH was basic, both the membrane and solute had negative charges, resulting in an increased ability to retain phenol. On the other hand, when the support membrane was coated with formaldehyde-cross-linked polyvinyl alcohol, the correlation of the rejection pattern changed considerably, leading to high rejection rates at acidic pH levels [134,135].

4.5. *Factors affecting the physical properties and performance of coal fly ash based ceramic membranes*

The mean pore size, porosity, flexural strength, and permeability of coal fly ash based ceramic membrane can be affected significantly by several factors such as sintering temperature, dosage of the pore-forming agent, particle size of coal fly ash, and dosage of binding additives, as indicated by several studies. In contrast, numerous experiments have shown that when operating conditions change, ceramic membranes made of coal fly ash does not crack. However, the precise trend of variation of these factors with properties and performance could not be established, as a result of the involvement of other factors that influence both the performance and properties of coal fly ash based ceramic membrane [98]. Therefore, major factors that need optimization in the fabrication of coal fly ash ceramic membrane are highlighted in this section.

4.5.1. *Effect of sintering temperature on the properties of coal fly ash ceramic membranes*

The properties of coal fly ash ceramic membranes are affected by the sintering temperature. Singh and Bulasara [82] examined how the sintering temperature affects the properties of a ceramic membrane made from coal fly ash. The membranes were sintered at 800, 850, 900, and 1000 °C. The physical characteristics of the coal fly ash ceramic membrane, including color, tensile strength, crystal phase, pore size, and porosity, were observed to be impacted by changes in the sintering temperature. The results showed that the average pore size only increased for the membrane sintered at 1000 °C whereas it decreased for sintering temperatures up to 900 °C (Fig. 9a). Except for those sintered at 1000 °C, as shown in Fig. 9b, the sintered membranes all had similar colors. Fig. 9c shows that



(a)

Sintering temperature (°C)	Minimum pore size (μm)	Maximum pore size (μm)	Average pore size (μm)
800	0.271	5.602	1.524
850	0.336	4.891	1.458
900	0.399	13.689	1.202
1,000	0.636	9.634	2.301

Fig. 9. (a)Variation of average pore size with sintering temperature, (b) picture of membranes sintered at four different temperatures, (c) variation of flexural strength with sintering temperature (d) XRD spectra at different sintering temperatures, and (e) variation of porosity with sintering temperature [82].

when sintering temperature increased, mechanical strength also increased. Continuous phase transitions occur during the sintering process, as shown by a comparison of the XRD patterns of various samples (Fig. 9d). The membrane sintered at 1000 °C lost anorthite, which was a significant component in the other four samples. Throughout the sintering process, other phases underwent changes and their contents changed as well. The membranes' porosity dropped from 38.1 to 34.8 % when the sintering temperature rose from 800 to 900 °C. However, the porosity of the membranes increased significantly to 39.7 % when sintered at 1000 °C Fig. 9e.

4.5.2. *Effect of pore forming agent dosage on the properties of coal fly ash ceramic membrane*

Pore-forming agents are essential in improving the permeability of ceramic membranes by changing the morphology and porosity of the pores. These pore-forming agents can be either inorganic or organic compounds that decompose at high temperatures. Cui et al. [87] studied the effect of pore-forming agent dosage on the characteristics of coal fly ash ceramic membrane. Spherical graphite was used as a pore-forming agent in their investigation, and the dosage was altered as wt%. The results demonstrated that as the dosage increased, many pores developed and were linked together to generate holes. As a result, water absorption and permeability flow improved. Liang et al. [84] also investigated the effect of pore forming agent dosage on the properties of coal fly ash ceramic membrane. They used dextrin as the pore-forming agent, with compositions of 0, 3, 6 and 9 wt% ($D_{50} = 7$ μm, $C_{6n}H_{10n}O_{5n}xH_2O$, and $\rho = 1.8$ g/cm^3). The experimental results indicated that the pore-forming agent content and mechanical strength of the samples are essentially inversely correlated (Fig. 10a). Additionally, the results demonstrated that when the dextrin concentration increases, more pores appear in the ceramic membranes made of tubular coal fly ash, resulting in a more porous structure, as seen in the SEM micrograph in Fig. 10b. The average pore size showed a trend of initially increasing and then decreasing with increasing pore-forming agent content, reaching its maximum value when the quantity is 6 wt%. The decrease of average pore size when the pore-forming agent level reaches 9 wt% was attributed to the strong binding action of dextrin. All the aforementioned studies revealed that altering the dosage of the pore-forming agent does not affect the development of cracks in the ceramic membrane made of coal fly ash. Suresh et al. [136] also investigated the effect of pore-forming agents on mechanical strength and porosity of the fabricated membrane. In their study, coal fly ash was used as the main precursor and a mixture of corn oil, waste cooking oil and starch solution as the pore forming agent. The results showed that porosity increased with increasing dosage of the pore-forming agent which corresponded to a decrease in mechanical strength.

4.5.3. *Effect of particle size of coal fly ash on the properties of coal fly ash ceramic membrane*

Particle size optimization of starting materials is key in the manufacturing of ceramic membrane as it helps maintain material consistency. Particle size has a significant influence on the mechanical and physical properties of ceramic membrane such as pore size, post-sintering shrinkage, bending strength, microstructural morphology, and porosity [137–140]. The effect of coal fly ash particle size on the porosity, pore size, microstructure and mechanical strength of synthesized coal fly ash based ceramic membrane has been investigated [104]. The experimental results showed that, a membrane with a denser structure and less porosity is produced when coal fly ash has a wider particle size distribution. As particle size increases, the membrane's pores get bigger while mechanical strength gets weaker. Large particles in the fly ash play a significant role in the mechanical strength of the ceramic membrane because they produce cracks in the membrane.

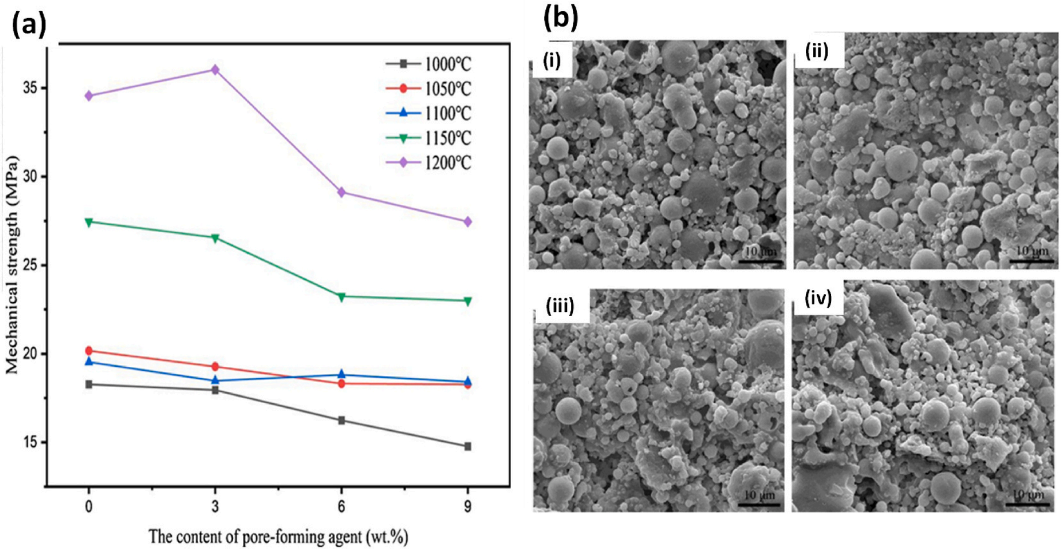


Fig. 10. (a) Relationship between the mechanical strength of the membrane and the content of the pore-forming agent as well as the temperature of sintering. (b) SEM images of Coal fly ash ceramic membrane with Wt% of dextrin (i) 0, (ii) 3, (iii) 6, and (iv) 9 sintered at 1150 °C [84].

4.5.4. Effect of binder dosage on the properties of coal fly ash ceramic membrane

Binders are used to hold ceramic particles together. Goswami et al. [141] investigated how the amount of binder affected the characteristics of a ceramic membrane made from coal fly ash by extrusion technique. Fly ash was used as the basic material (75 %), together with the necessary amounts of quartz (20 %), calcium carbonate (5 %), and sodium salts of carboxymethyl cellulose acting as binders, to create tubular ceramic membranes. The results revelled that, a higher binder concentration causes agglomeration in the membrane matrix, which results in the creation of big, irregular holes. With a rise in binder concentration, the membranes' mechanical strength considerably decreased. In addition, the results showed that an increase in binder concentration had a detrimental effect on the membrane's chemical stability.

4.6. Factors that affect separation efficiency of coal fly ash-based ceramic membranes

The surface characteristics of the ceramic membrane (surface wettability and surface charge), the solution properties (pH, temperature, viscosity), and the operation parameters (pressure difference, flow rate, and time) are key variables that determine the separation effectiveness of ceramic membranes [35,142]. Surface charge of coal fly ash based ceramic membranes have an impact on how pollutants interact with the membrane surface, which has an influence on the ceramic membrane's permeability and rejection capabilities [143–145]. Higher membrane flux and improved antifouling properties occur when membrane surface charge is similar to contaminants charge due to the repulsive effect of similar charge [146]. Contrarily, opposing charges cause electrostatic interactions between contaminants and membranes, which have a major negative impact on the effectiveness of separation and on membrane anti-fouling properties [147,148]. The pH of the filtration feed has a significant impact on the surface charge of the membranes [149].

The separation effectiveness of coal fly ash based ceramic membrane is also impacted by the presence of inorganic ions in the contaminants matrices. This results from these ions' ability to alter the surface charge of membrane surfaces and contaminants [150]. Alventosa-deLara et al. [151] studied the effects of the feed salt concentration on the removal of organic dyes by ultrafiltration ceramic membranes. The results showed increased overall resistance and decreased dye rejection by the ceramic membrane in the presence of NaCl. This occurred as a result of the Na^+ ion neutralization of the membrane surface charge and allowing more dye particles to pass through.

Hydrophobicity and hydrophilicity of coal fly ash based ceramic membrane surfaces affect separation effectiveness of the membrane [131]. This is due to the correlation between contact angle values and ceramic membrane morphology and pore size [152]. Surface wettability has an impact on how membranes are utilized, with hydrophilic membranes frequently employed in water filtration and hydrophobic membranes excellent for membrane distillation [153]. For instance, Zhang et al. [34] fabricated hydrophobic coal fly ash based ceramic membrane for desalination. The membrane showed excellent water flux and higher salt rejection compared to aluminium based ceramic membranes. Surface geometrical structure or surface free energy can be modified to alter the wettability of membrane surfaces [34,106,154]. Zhang et al. [80] studied the effect of changing wettability of the surface of a coal fly ash based ceramic membrane. In their study the ceramic membrane was modified from hydrophilic to hydrophobic through immersion of 1H,1H,2H,2H-perfluorodecyltriethoxysilane (FC8) on the surface of the membrane. The results demonstrated that the final super hydrophobic membrane outperformed hydrophilic ones in terms of self-cleaning. The physical and chemical characteristics of the materials being separated, such as viscosity, charge, stability, and solubility, can be influenced by temperature and pH [155,156]. This could impact on the diffusion rate across the membrane pores. The fouling behaviour of the contaminants was also influenced by temperature [157].

4.7. Management of fouling on coal fly ash based ceramic membranes

There have been numerous investigations on the physical and chemical deposition or adsorption of microbiological, organic, and inorganic compounds onto membrane pores or onto the membrane surface. This causes the membrane pores to contract or clog thereby reducing permeability and raising the flow resistance, which has an impact on the quantity and quality of treated effluent [158,159]. This dramatically lowers the lifespan and separation effectiveness of these membranes [160,161]. Not many reports are available on how to clean the fouled coal fly ash based ceramic membrane. Therefore, the main reasons, preventative measures, and methods for cleaning fouled ceramic membranes are all discussed in this section.

Reversible fouling, which often forms on the membrane surface, and irreversible fouling, which refers to internal fouling in the membrane pores, are the two subgroups of membrane fouling [162]. Ceramic membrane fouling is primarily a function of the properties and performance of ceramic membranes, operational conditions as well as the characteristics and nature of the filtering feed. These membrane properties include roughness, wettability, surface charge, and membrane pore size [160,163]. Foulant type (inorganic salts, metal oxides, natural organic matter, manufactured organic matter, and microbiological contaminants), concentration, pH, charge, and ionic strength are some of the properties of the feed. Fouling of ceramic membranes is influenced by a number of operating factors, including flow rate, temperature, and pressure. Coal fly ash is less likely to get irreversible fouling than organic membranes because it is predominantly composed of metallic oxides, which have strong hydrophilicity and chemical stability [163,164]. However, reversible fouling of coal fly ash or other ceramic based membranes are major obstacles to their use in wastewater treatment.

Fouling raises operational costs because it necessitates higher pressures to maintain permeate flux, uses more energy, requires more time to clean, and costs more to replace the membrane [165,166]. Therefore, specific steps must be taken to either prevent fouling or clean the fouled membrane in order to restore and maintain membrane flux, extend the cleaning cycle, and prolong the lifespan of ceramic membranes [167]. Pre-treating influents with sacrificial membranes or another type of treatment method before ceramic membrane filtration, optimizing operational parameters, controlling the feed solution's properties, and using a pre-coat layer on the membrane are all actions that reduce fouling [162,168]. Combining different processes, such as advanced oxidation with ceramic membrane technology can also lessen fouling through changing properties of ceramic membranes and enhancing separation efficiency. Ceramic membrane surfaces that have been dip-coated with nanoparticles are an example of how the surfaces are modified [33]. Bao et al. [169] studied how to get rid of fouling by coating the ceramic membrane with cobalt oxide. The cobalt oxide was ensured not to leak into the pores of the ceramic membrane by the development of the Co–*O*–Al bond on its surface. The results of the study showed that ceramic membrane functionalized with cobalt oxide have antifouling properties. The pollutant's intrinsic catalytic decomposition by the metal oxide may be the cause of the antifouling qualities since it keeps the pollutant from passing untreated through the ceramic barrier.

Ceramic membrane fouling can be eliminated through cleaning procedures such as chemical, physical, electrical, and vibration. All these methods do not guarantee the complete regeneration of ceramic membranes. Chemical cleaning uses chemicals such as acids, surfactants, oxidizing agents, chelating agents, and alkali to clean ceramic membrane pores and surfaces [160,170,171]**.** This approach can be used to independently or in conjunction with physical cleaning techniques. Although chemical cleaning is a common cleaning approach, it has a number of negative aspects, including harm to the environment, membrane degradation, cost due to the high cost of cleaning chemicals, and the tendency to alter the nature of the foulants [162,172]. Back washing and mechanical scraping of contaminants on the membrane surface and pores are examples of physical cleaning methods. The most common of these techniques is back washing. It entails washing the membrane against the direction of the typical flux of membrane penetrates. However, according to Zielińska [173]**,** this method can harm the ceramic membrane structure. The ideal strategy for cleaning ceramic membranes is combining cleaning techniques that work in conjunction. This is due to the fact that different ceramic membranes foulants, such as inorganic salts, metal oxides, naturally occurring organic matter, synthetically produced organic matter, and microbiological contaminants have distinct properties [174].

5. Coal fly ash based ceramic membrane cost analysis

Ceramic membrane fabrication by commercial starting materials such as silicon carbide, stainless steel, aluminium, zirconium oxide and silicon nitride are very expensive. Their cost price ranges from \$500–3000/m^2 with the price of polymeric membranes ranging from \$20–200/m^2 [175,176]. The preparation of ceramic membranes from these materials also requires high sintering temperatures (1300–1700 °C) which also makes the production process costly [177]. Ceramic membranes offer lower operating costs than polymeric membranes due to their longer lifespan, simplicity of cleaning by high-temperature steam sterilization, and capacity to restore initial permeability and water flux by reverse flushing and proper cleaning [178]. One of the main factors that have made the use of coal fly ash in the production of ceramic membranes popular is their low production cost as shown in Table 3. The inexpensive production costs of coal fly ash based ceramic membranes is one of the paramount reasons why it is so common to use it in the fabrication of ceramic membranes. Therefore, the use of coal fly ash as a ceramic membrane starting material is considered a viable solution. Coal fly ash cost price ranges from \$25 to \$250/m^2. The six ceramic membranes shown in Table 3 have significantly variable production cost prices because various expenses during the fabrication of the coal fly ash-based ceramic membrane were taken into account. The most complete production cost pricing should include the cost of starting materials, processing costs, maintenance expenses, labour costs, and electricity expenses [179]. The estimated production cost of a coal fly ash-based ceramic membrane fabricated by Suresh et al. [136] was USD525/m^2. In their cost analysis studies, they factored in various parameters associated with the cost of coal fly ash, cost of additives, manpower, electricity and equipment. In another similar study, Goswami et al. [180] fabricated a coal fly ash ceramic membrane and the cost price of a unit membrane was estimated by considering several expenses as shown in Fig. 11. The estimated unit cost price established was USD 250/m^2. Lower sintering temperatures and coal fly ash pricing are the two main factors that dramatically lower production costs [181].

6. Conclusions and future prospects

The use of coal fly ash in membrane technology has garnered much attention because of its low sintering temperature, high surface area, low initial cost, and significant active functional groups, which primarily consist of SiO_2 and Al_2O_3. Additionally, the use of coal fly ash marks a significant advancement in waste management. Hence, heavy metals from coal fly ash should be removed before ceramic membrane fabrication to ensure safety and environmental sustainability for long-term use. Despite the promising outcomes associated with the use of coal fly ash as membrane precursors, sintering additives, membrane supports, membrane fillers, and

Table 3
Cost of different coal fly ash based ceramic membranes.

Coal fly based ceramic membrane	Production cost price (USD/m^2)	Reference
Novel fly ash blended ceramic membrane in MFC	35.76	[46]
Coal fly ash ceramic membrane	25	[178]
Defective analcime/geopolymer composite membrane derived from fly ash	31.8	[182]
Fly ash-based low-cost tubular ceramic membrane	250	[180]
Low-cost microfiltration membranes from fly ash	17	[82]
Fly ash based ceramic microfiltration membranes for oil-water emulsion treatment	225	[136]

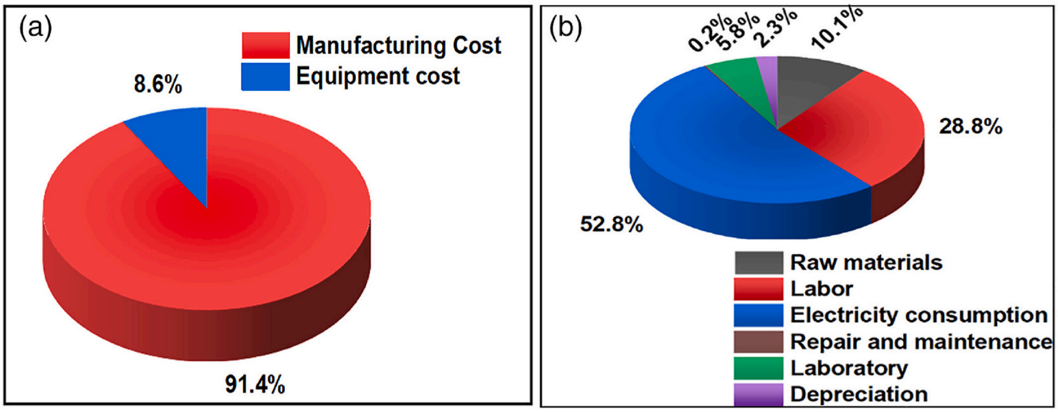


Fig. 11. (a) Fabrication cost of coal fly ash based ceramic membrane as percentages of manufacturing cost and equipment cost and (b) factored in manufacturing expenses [180].

membrane filters in membrane technology, their full-scale application has not been thoroughly investigated and implemented. Numerous studies have found that the use of ceramic membranes made from coal fly ash has effectively reduced turbidity, dye and heavy metal concentrations, total dissolved solids, sea desalination, and oil content of wastewater. Therefore, laboratory studies must be scaled up to explore the viability of pilot plants with full consideration of aspects that affect their efficiency and durability to advance the many uses of coal fly ash in membrane technology. To lower the fabrication cost, which is the primary factor affecting the full utilization of ceramic membranes, research should continue to look for relatively affordable and easily accessible materials rich in chemical composition that are essential in the fabrication of ceramic membranes. They could then be used as composites with coal fly ash or serve different roles in membrane preparations. The antifouling potential of ceramic membranes fabricated from coal fly ash should be enhanced to promote the effectiveness of ceramic membrane technology in the treatment of wastewater.

Data availability

Data used for this study will be made available upon request.

CRediT authorship contribution statement

Lawrence Sawunyama: Writing – original draft, Formal analysis. **Olalekan C. Olatunde:** Writing – original draft, Formal analysis. **Opeyemi A. Oyewo:** Writing – review & editing, Supervision. **Mokgadi F. Bopape:** Writing – review & editing, Supervision. **Damian C. Onwudiwe:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Damian Onwudiwe reports administrative support was provided by North-West University - Mafikeng Campus. Damian Onwudiwe reports a relationship with Elsevier B.V. that includes: Editorial board membership. Not applicable has patent Not applicable pending to Not applicable. Editorial Board Member of Heliyon-Materials If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] M.A. Onu, et al., Challenges of Wastewater Generation and Management in Sub-saharan Africa: A Review, Environmental Challenges, 2023 100686.
[2] J.N. Zvimba, et al., Energy pathway for transitioning to a circular economy within wastewater services, Case Studies in Chemical and Environmental Engineering 4 (2021) 100144.
[3] L. Sawunyama, et al., Photocatalytic degradation of tetracycline using surface defective black TiO2–ZnO heterojunction photocatalyst under visible light, Heliyon 9 (11) (2023).
[4] C. Cossio, et al., Wastewater management in small towns–understanding the failure of small treatment plants in Bolivia, Environ. Technol. 39 (11) (2018) 1393–1403.
[5] K. Obaideen, et al., The role of wastewater treatment in achieving sustainable development goals (SDGs) and sustainability guideline, Energy Nexus 7 (2022) 100112.
[6] R. Saxena, M. Saxena, A. Lochab, Recent progress in nanomaterials for adsorptive removal of organic contaminants from wastewater, ChemistrySelect 5 (1) (2020) 335–353.
[7] R. Sangamnere, et al., A critical review of conventional and emerging wastewater treatment technologies, Sustainable Water Resources Management 9 (2) (2023) 58.

[8] Y. Geng, et al., Implementing China's circular economy concept at the regional level: a review of progress in Dalian, China, Waste Manag. 29 (2) (2009) 996–1002.
[9] S. Ahmed, et al., Recent developments in physical, biological, chemical, and hybrid treatment techniques for removing emerging contaminants from wastewater, J. Hazard Mater. 416 (2021) 125912.
[10] T. Shindhal, et al., A critical review on advances in the practices and perspectives for the treatment of dye industry wastewater, Bioengineered 12 (1) (2021) 70–87.
[11] M. Priyadarshini, S. Sathe, M.M. Ghangrekar, Hybrid Treatment Solutions for Removal of Micropollutant from Wastewaters. Microconstituents in the Environment: Occurrence, Fate, Removal and Management, 2023, pp. 491–512.
[12] G. Crini, E. Lichtfouse, Advantages and disadvantages of techniques used for wastewater treatment, Environ. Chem. Lett. 17 (2019) 145–155.
[13] M. Sun, et al., Electrified membranes for water treatment applications, ACS ES&T Engineering 1 (4) (2021) 725–752.
[14] F. El Moukhtari, L. Martín-Pozo, A. Zafra-Gómez, Strategies based on the use of microorganisms for the elimination of pollutants with endocrine-disrupting activity in the environment, J. Environ. Chem. Eng. (2023) 109268.
[15] R. Singh, N. Hankins, Emerging Membrane Technology for Sustainable Water Treatment, Elsevier, 2016.
[16] M. Kotobuki, et al., Ceramic-polymer composite membranes for water and wastewater treatment: Bridging the big gap between ceramics and polymers, Molecules 26 (11) (2021) 3331.
[17] L. Sawunyama, et al., Ceramic-polymer composite membranes: synthesis methods and environmental applications, Ceram. Int. 50 (2024) 5067–5079.
[18] S.F. Ahmed, et al., Strategies to improve membrane performance in wastewater treatment, Chemosphere (2022) 135527.
[19] M. Binazadeh, et al., An overview of Photocatalytic membrane degradation development, Materials 16 (9) (2023) 3526.
[20] E.P.N. Ntone, et al., A Mini review on membrane potential for pharmaceutical and personal care product (PPCP) removal from water, Water, Air, Soil Pollut. 234 (7) (2023) 412.
[21] Y. Zhang, et al., Preparation of ceramic membranes and their application in wastewater and water treatment, Water 15 (19) (2023) 3344.
[22] Omar, N.M.A., et al., Recent Progress and Technical Improvement Strategies for Mitigating Ceramic Membrane Bottlenecks in Water Purification Processes: A Review. International Journal of Applied Ceramic Technology..
[23] S. Sonawane, et al., Nanomaterials for membrane synthesis: introduction, mechanism, and challenges for wastewater treatment, in: Handbook of Nanomaterials for Wastewater Treatment, Elsevier, 2021, pp. 537–553.
[24] S. Ismail, et al., Extracellular polymeric substances (EPS) in upflow anaerobic sludge blanket (UASB) reactors operated under high salinity conditions, Water Res. 44 (6) (2010) 1909–1917.
[25] W.N.W. Salleh, et al., Precursor selection and process conditions in the preparation of carbon membrane for gas separation: a review, Separ. Purif. Rev. 40 (4) (2011) 261–311.
[26] N. Shehata, et al., Membrane-based water and wastewater treatment technologies: issues, current trends, challenges, and role in achieving sustainable development goals, and circular economy, Chemosphere 320 (2023) 137993.
[27] S. Sarp, N. Hilal, Membrane-based Salinity Gradient Processes for Water Treatment and Power Generation, Elsevier, 2018.
[28] M.W. Hakami, et al., Ceramic microfiltration membranes in wastewater treatment: filtration behavior, fouling and prevention, Membranes 10 (9) (2020) 248.
[29] P. Goh, A. Ismail, A review on inorganic membranes for desalination and wastewater treatment, Desalination 434 (2018) 60–80.
[30] A. Samadi, et al., Waste-derived low-cost ceramic membranes for water treatment: opportunities, challenges and future directions, Resour. Conserv. Recycl. 185 (2022) 106497.
[31] M.B. Asif, Z. Zhang, Ceramic membrane technology for water and wastewater treatment: a critical review of performance, full-scale applications, membrane fouling and prospects, Chem. Eng. J. 418 (2021) 129481.
[32] Lin, B., S. Heijman, and L. Rietveld, Effect of oxidation on surface interactions in relation to fouling behaviour of ceramic membranes: a review. CATALYTIC CERAMIC NANOFILTRATION FOR DIRECT SURFACE WATER TREATMENT AND FENTON CLEANING: p. 27..
[33] C. Li, et al., Ceramic nanocomposite membranes and membrane fouling: a review, Water Res. 175 (2020) 115674.
[34] Z. Zhang, et al., Development of hydrophobic coal-fly-ash-based ceramic membrane for vacuum membrane distillation, Materials 16 (8) (2023) 3153.
[35] E. Drioli, L. Giorno, E. Fontananova, Comprehensive Membrane Science and Engineering, Elsevier, 2017.
[36] M. Lee, Z. Wu, K. Li, Advances in ceramic membranes for water treatment, in: Advances in Membrane Technologies for Water Treatment, Elsevier, 2015, pp. 43–82.
[37] Drioli, E., L. Giorno, and E. Fontananova, Membrane Operations in Advanced Molecular Separations. (No Title)..
[38] M.-M. Lorente-Ayza, et al., On the underestimated effect of the starch ash on the characteristics of low cost ceramic membranes, Ceram. Int. 42 (16) (2016) 18944–18954.
[39] Z. He, et al., Ceramic-based membranes for water and wastewater treatment, Colloids Surf. A Physicochem. Eng. Asp. 578 (2019) 123513.
[40] F. Azaman, et al., Review on natural clay ceramic membrane: fabrication and application in water and wastewater treatment, Malays. J. Fundam. Appl. Sci 17 (2021) 62–78.
[41] L. Sun, Z. Wang, B. Gao, Ceramic membranes originated from cost-effective and abundant natural minerals and industrial wastes for broad applications—a review, Desalin. Water Treat 201 (2020) 121–138.
[42] H. Aloulou, et al., Development of ultrafiltration kaolin membranes over sand and zeolite supports for the treatment of electroplating wastewater, Membranes 12 (11) (2022) 1066.
[43] N. Malik, V.K. Bulasara, S. Basu, Preparation of novel porous ceramic microfiltration membranes from fly ash, kaolin and dolomite mixtures, Ceram. Int. 46 (5) (2020) 6889–6898.
[44] S.S. Hossain, P. Roy, Sustainable ceramics derived from solid wastes: a review, Journal of Asian Ceramic Societies 8 (4) (2020) 984–1009.
[45] L. Sawunyama, et al., Metal oxide functionalized ceramic membranes for the removal of pharmaceuticals in wastewater, Surface. Interfac. (2023) 102787.
[46] A. Rao, et al., Characterization and application of novel fly ash blended ceramic membrane in MFC for low-cost and sustainable wastewater treatment and power generation, Environ. Sci. Pollut. Control Ser. 30 (16) (2023) 45872–45887.
[47] J. Fu, et al., Mullite whisker-constructed ceramic membranes prepared from fly ash by in-situ catalytic reaction, Mater. Chem. Phys. 308 (2023) 128280.
[48] D. Das, et al., Recycling of coal fly ash for fabrication of elongated mullite rod bonded porous SiC ceramic membrane and its application in filtration, J. Eur. Ceram. Soc. 40 (5) (2020) 2163–2172.
[49] A. Abdullayev, et al., Materials and applications for low-cost ceramic membranes, Membranes 9 (9) (2019) 105.
[50] H. Zhou, et al., Towards Sustainable Coal Industry: Turning Coal Bottom Ash into Wealth, vol. 804, Science of the Total Environment, 2022 149985.
[51] F. Mushtaq, et al., Possible applications of coal fly ash in wastewater treatment, J. Environ. Manag. 240 (2019) 27–46.
[52] N. Ghazali, K. Muthusamy, S. Wan Ahmad, Utilization of fly ash in construction, in: IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2019.
[53] M. Rossow, Fly Ash Facts for Highway Engineers, New York NY Continuing Education and Development, 2003.
[54] A. Dwivedi, M.K. Jain, Fly ash–waste management and overview: a Review, Recent Res. Sci. Technol. 6 (1) (2014).
[55] A. Labidi, et al., Coal ash for removing toxic metals and phenolic contaminants from wastewater: a brief review, Crit. Rev. Environ. Sci. Technol. (2023) 1–24.
[56] S. Wang, H. Wu, Environmental-benign utilisation of fly ash as low-cost adsorbents, J. Hazard Mater. 136 (3) (2006) 482–501.
[57] M. Jaishankar, et al., Toxicity, mechanism and health effects of some heavy metals, Interdiscipl. Toxicol. 7 (2) (2014) 60.
[58] R. Matjie, J. Bunt, J. Van Heerden, Extraction of alumina from coal fly ash generated from a selected low rank bituminous South African coal, Miner. Eng. 18 (3) (2005) 299–310.
[59] S.M.H. Asl, et al., Porous catalysts fabricated from coal fly ash as cost-effective alternatives for industrial applications: a review, Fuel 217 (2018) 320–342.
[60] S.V. Vassilev, C.G. Vassileva, A new approach for the classification of coal fly ashes based on their origin, composition, properties, and behaviour, Fuel 86 (10–11) (2007) 1490–1512.

[61] R. Blissett, N. Rowson, A review of the multi-component utilisation of coal fly ash, Fuel 97 (2012) 1–23.

[62] N. Vig, S. Mor, K. Ravindra, The multiple value characteristics of fly ash from Indian coal thermal power plants: a review, Environ. Monit. Assess. 195 (1) (2023) 33.

[63] C. Wang, et al., High value-added applications of coal fly ash in the form of porous materials: a review, Ceram. Int. 47 (16) (2021) 22302–22315.

[64] Y.G. Adewuyi, Recent advances in fly-ash-based geopolymers: potential on the utilization for sustainable environmental remediation, ACS Omega 6 (24) (2021) 15532–15542.

[65] S.S. Panda, B. Jena, Yield behaviour of two-way reinforced concrete flyash brick slab, in: Recent Developments in Sustainable Infrastructure: Select Proceedings of ICRDSI, Springer, 2019, p. 2021.

[66] A.R. Gollakota, V. Volli, C.-M. Shu, Progressive utilisation prospects of coal fly ash: a review, Sci. Total Environ. 672 (2019) 951–989.

[67] S.C. Openshaw, Utilization of Coal Fly Ash, FLORIDA UNIV GAINESVILLE, 1992.

[68] Y. Jin, et al., Structure refinement of fly ash in connection with its reactivity in geopolymerization, Waste Manag. 118 (2020) 350–359.

[69] M.L.D. Jayaranjan, E.D. Van Hullebusch, A.P. Annachhatre, Reuse options for coal fired power plant bottom ash and fly ash, Rev. Environ. Sci. Biotechnol. 13 (2014) 467–486.

[70] S. Kelechi, et al., A comprehensive review on coal fly ash and its application in the construction industry, Cogent Engineering 9 (1) (2022) 2114201.

[71] H. Feuerborn, D. Harris, C. Heidrich, Global aspects on coal combustion products, in: Proceeds of the world of coal ash (WOCA)St. Louis, MO, USA, 2019, pp. 25–33.

[72] R. Nsiah-Gyambibi, et al., Valorization of coal fly ash (CFA): a multi-industry review, Int. J. Environ. Sci. Technol. (2023) 1–16.

[73] C.R. Shearer, The Productive Reuse of Coal, Biomass and Co-fired Fly Ash, Georgia Institute of Technology, 2014.

[74] IEA Coal 2020 (2020).

[75] T.O. Ajiboye, et al., Synthesis approaches to ceramic membranes, their composites, and application in the removal of tetracycline from water, Environmental Advances (2023) 100371.

[76] A.K. Dan, et al., Prospective utilization of coal fly ash for making advanced materials, in: Clean Coal Technologies: Beneficiation, Utilization, Transport Phenomena and Prospective, Springer, 2021, pp. 511–531.

[77] W. Peng, et al., Toxicity of coal fly ash and coal gangue leachate to Daphnia magna: focusing on typical heavy metals, J. Clean. Prod. 330 (2022) 129946.

[78] M. Issaoui, L. Limousy, Low-cost ceramic membranes: synthesis, classifications, and applications, Compt. Rendus Chem. 22 (2–3) (2019) 175–187.

[79] D. Das, N. Kayal, Influence of additive contents on the properties of SiC ceramic membranes and their performance in oil-water separation, Int. J. Appl. Ceram. Technol. 20 (3) (2023) 1715–1729.

[80] H. Fu, et al., Preparation, characterization and properties study of a superhydrophobic ceramic membrane based on fly ash, Ceram. Int. 48 (8) (2022) 11573–11587.

[81] F. Jiang, et al., Formation mechanism of high apparent porosity ceramics prepared from fly ash cenosphere, J. Alloys Compd. 749 (2018) 750–757.

[82] G. Singh, V.K. Bulasara, Preparation of low-cost microfiltration membranes from fly ash, Desalination Water Treat. 53 (5) (2015) 1204–1212.

[83] A. Agarwal, et al., Synthesis, characterization and performance studies of kaolin-fly ash-based membranes for microfiltration of oily waste water, J. Petrol. Sci. Eng. 194 (2020) 107475.

[84] D. Liang, et al., Influence of dextrin content and sintering temperature on the properties of coal fly ash-based tubular ceramic membrane for flue gas moisture recovery, J. Eur. Ceram. Soc. 41 (11) (2021) 5696–5710.

[85] J. Huang, et al., Recycle coal fly ash for preparing tubular ceramic membranes applied in transport membrane condenser, Separ. Purif. Technol. 282 (2022) 119972.

[86] Z. Wei, J. Hou, Z. Zhu, High-aluminum fly ash recycling for fabrication of cost-effective ceramic membrane supports, J. Alloys Compd. 683 (2016) 474–480.

[87] Z. Cui, et al., Preparation of porous mullite ceramic supports from high alumina fly ash, J. Mater. Cycles Waste Manag. 25 (2) (2023) 1120–1129.

[88] P. Monash, G. Pugazhenthi, P. Saravanan, Various fabrication methods of porous ceramic supports for membrane applications, Rev. Chem. Eng. 29 (5) (2013) 357–383.

[89] E. Apriyanti, H. Susanto, I.N. Widiasa, Development of fly ash coal/TiO2 pored composite materials in the making of ceramic membrane for water treatment process, in: IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2021.

[90] J. Liu, et al., Feasible recycling of industrial waste coal fly ash for preparation of anorthite-cordierite based porous ceramic membrane supports with addition of dolomite, J. Eur. Ceram. Soc. 36 (4) (2016) 1059–1071.

[91] R. Chathurappan, A. Jayapal, Synthesis and characterization of coal fly ash based multipurpose ultrafiltration membrane, Materialia 25 (2022) 101548.

[92] P. Fan, et al., Preparation and development of porous ceramic membrane supports fabricated by extrusion technique, Chemical Engineering Transactions 55 (2016) 277–282.

[93] M. Ağtaş, M. Dilaver, İ. Koyuncu, Ceramic membrane overview and applications in textile industry: a review, Water Sci. Technol. 84 (5) (2021) 1059–1078.

[94] I. Jedidi, et al., Preparation of a new ceramic microfiltration membrane from mineral coal fly ash: application to the treatment of the textile dying effluents, Powder Technol. 208 (2) (2011) 427–432.

[95] I. Jedidi, et al., Elaboration of new ceramic microfiltration membranes from mineral coal fly ash applied to waste water treatment, J. Hazard Mater. 172 (1) (2009) 152–158.

[96] J.-M. Kim, et al., Fabrication of transparent MgAl2O4 spinel through homogenous green compaction by microfluidization and slip casting, Ceram. Int. 41 (10) (2015) 13354–13360.

[97] J. Fang, et al., Preparation and characterization of tubular supported ceramic microfiltration membranes from fly ash, Separ. Purif. Technol. 80 (3) (2011) 585–591.

[98] K.P. Goswami, K. Pakshirajan, G. Pugazhenthi, Process Intensification through Waste Fly Ash Conversion and Application as Ceramic Membranes: A Review, vol. 808, Science of The Total Environment, 2022 151968.

[99] R.K. Nishihora, et al., Manufacturing porous ceramic materials by tape casting—a review, J. Eur. Ceram. Soc. 38 (4) (2018) 988–1001.

[100] S.K. Hubadillah, et al., Fabrications and applications of low cost ceramic membrane from kaolin: a comprehensive review, Ceram. Int. 44 (5) (2018) 4538–4560.

[101] R.E. Mistler, E.R. Twiname, Tape Casting: Theory and Practice, American ceramic society, 2000.

[102] L. Cheng, et al., Structure design, fabrication, properties of laminated ceramics: a review, International Journal of Lightweight Materials and Manufacture 1 (3) (2018) 126–141.

[103] M. Fu, et al., Waste recycling of coal fly ash for design of highly porous whisker-structured mullite ceramic membranes, J. Eur. Ceram. Soc. 39 (16) (2019) 5320–5331.

[104] J. Huang, et al., Effects of particle size on microstructure and mechanical strength of a fly ash based ceramic membrane, Ceram. Int. 49 (2023) 15655–15664.

[105] M.R. de la Rocha, et al., Preparation of alumina based tubular asymmetric membranes incorporated with coal fly ash by centrifugal casting, Ceram. Int. 47 (3) (2021) 4187–4196.

[106] L. Zhu, et al., Coal fly ash industrial waste recycling for fabrication of mullite-whisker-structured porous ceramic membrane supports, RSC Adv. 5 (15) (2015) 11163–11174.

[107] K. Suresh, Recycling of fly ash for development of value added products, Mater. Today: Proc. 46 (2021) 5666–5674.

[108] H.W. Nugteren, M. Janssen-Jurkovícová, B. Scarlett, Removal of heavy metals from fly ash and the impact on its quality, J. Chem. Technol. Biotechnol. 77 (3) (2002) 389–395.

[109] X. Peng, et al., Enhanced electrokinetic removal of heavy metals in MSWI fly ash assisted by cation exchange membranes, Appl. Mech. Mater. (2011) 84–85.

[110] J. Bai, Fabrication and properties of porous mullite ceramics from calcined carbonaceous kaolin and α-Al2O3, Ceram. Int. 36 (2) (2010) 673–678.

[111] H. Guo, W. Li, F. Ye, Low-cost porous mullite ceramic membrane supports fabricated from kyanite by casting and reaction sintering, Ceram. Int. 42 (4) (2016) 4819–4826.

[112] C. Li, et al., Preparation and characterization of mullite whisker reinforced ceramics made from coal fly ash, Ceram. Int. 45 (5) (2019) 5613–5616.

[113] L. Zhu, et al., Ceramic-based composite membrane with a porous network surface featuring a highly stable flux for drinking water purification, Membranes 9 (1) (2019) 5.

[114] Y. Luo, et al., Preparation and characterization of whisker-reinforced ceramics from coal fly ash, Ceram. Int. 43 (1) (2017) 1–11. Part A).

[115] R. Siauciunas, et al., The sorption properties of tobermorite modified with Na+ and Al3+ ions, Ceramics 48 (2) (2004) 76–82.

[116] N.J. Coleman, D.S. Brassington, Synthesis of Al-substituted 11 A tobermorite from newsprint recycling residue: a feasibility study, Mater. Res. Bull. 38 (3) (2003) 485–497.

[117] A.P. Hurt, et al., Calcium silicate hydrate cation-exchanger from paper recycling ash and waste container glass, Ceramics 5 (2022) 301–317, https://doi.org/10.3390/ceramics5030024.

[118] L. Zhu, et al., Removal of Pb(II) from wastewater using Al2O3-NaA zeolite composite hollow fiber membranes synthesized from solid waste coal fly ash, Chemosphere 206 (2018) 278–284.

[119] N. Janani, et al., Influence of sintering additives on densification and Li+ conductivity of Al doped Li7La3Zr2O12 lithium garnet, RSC Adv. 4 (93) (2014) 51228–51238.

[120] Z. Li, C. Molin, S.E. Gebhardt, Influence of sintering Additives on modified (Ba,Sr)(Sn,Ti)O3 for electrocaloric application, Inorganics 11 (2023), https://doi.org/10.3390/inorganics11040151.

[121] D. Das, N. Kayal, M.D.d.M. Innocentini, Permeability behavior and wastewater filtration performance of mullite bonded porous SiC ceramic membrane prepared using coal fly ash as sintering additive, Trans. Indian Ceram. Soc. 80 (3) (2021) 186–192.

[122] R. Saranya, et al., Efficient rejection of organic compounds using functionalized ZSM-5 incorporated PPSU mixed matrix membrane, RSC Adv. 7 (25) (2017) 15536–15552.

[123] C. Lavanya, J. Kusuma, R. Geetha Balakrishna, Pyrochlores: oxygen-rich moieties as ceramic fillers in uplifting the antifouling property and dye removal capacity of polymeric membranes, Separ. Purif. Technol. 272 (2021) 118946.

[124] V.K. Jha, M. Matsuda, M. Miyake, Resource recovery from coal fly ash waste: an overview study, J. Ceram. Soc. Jpn. 116 (1350) (2008) 167–175.

[125] L.M. Manocha, G. Prasad, S. Manocha, Structural, mechanical and frictional studies on carbon-fly ash-ceramic composites, Trans. Indian Ceram. Soc. 71 (2) (2012) 86–94.

[126] K. Yang, et al., Comparison of two modified coal ash ferric-carbon micro-electrolysis ceramic media for pretreatment of tetracycline wastewater, Environ. Sci. Pollut. Control Ser. 24 (13) (2017) 12462–12473.

[127] K.P. Goswami, G. Pugazhenthi, Treatment of poultry slaughterhouse wastewater using tubular microfiltration membrane with fly ash as key precursor, J. Water Proc. Eng. 37 (2020) 101361.

[128] K.P. Goswami, G. Pugazhenthi, Treatment of starch-rich wastewater using fly ash-based low-cost tubular ceramic membrane, Environ. Prog. Sustain. Energy 41 (6) (2022) e13906.

[129] D. Zou, et al., A novel thermal spraying technique to fabricate fly ash/alumina composite membranes for oily emulsion and spent tin wastewater treatment, Separ. Purif. Technol. 219 (2019) 127–136.

[130] K. Suresh, G. Pugazhenthi, R. Uppaluri, Preparation and characterization of hydrothermally engineered TiO2-fly ash composite membrane, Front. Chem. Sci. Eng. 11 (2) (2017) 266–279.

[131] D. Zou, et al., One-step engineering of low-cost kaolin/fly ash ceramic membranes for efficient separation of oil-water emulsions, J. Membr. Sci. 621 (2021) 118954.

[132] J. Zhang, et al., An environment-friendly Fe3O4@CFAS porous ceramic: adsorption of Cu(II) ions and process optimisation using response surface methodology, Ceram. Int. 47 (6) (2021) 8256–8264.

[133] J. Zhang, et al., Simultaneous removal of Cu(II), Cd(II), Cr(VI), and rhodamine B in wastewater using TiO2 nanofibers membrane loaded on porous fly ash ceramic support, Separ. Purif. Technol. 272 (2021) 118888.

[134] V. Gupta, C. Raja, J. Anandkumar, Phenol removal by novel choline chloride blended cellulose acetate-fly ash composite membrane, Periodica Polytechnica Chemical Engineering 64 (1) (2020) 116–123.

[135] V. Gupta, J. Anandkumar, Synthesis of crosslinked PVA-ceramic composite membrane for phenol removal from aqueous solution, J. Serb. Chem. Soc. 84 (2) (2019) 211–224.

[136] K. Suresh, G. Pugazhenthi, R. Uppaluri, Fly ash based ceramic microfiltration membranes for oil-water emulsion treatment: parametric optimization using response surface methodology, J. Water Proc. Eng. 13 (2016) 27–43.

[137] K. Suresh, G. Pugazhenthi, Cross flow microfiltration of oil-water emulsions using clay based ceramic membrane support and TiO2 composite membrane, Egyptian journal of petroleum 26 (3) (2017) 679–694.

[138] X. Xu, et al., Effect of SiC particle size on properties of SiC porous ceramics, Journal of Wuhan University of Technology-Mater. Sci. Ed. 37 (1) (2022) 13–22.

[139] C. Qian, et al., The effect of particle size distribution on the microstructure and properties of Al2O3 ceramics formed by stereolithography, Ceram. Int. 48 (15) (2022) 21641–21650.

[140] S. Moore, How Is Particle Size Analysis Used in Ceramics? AZoM, 2021.

[141] K.P. Goswami, G. Pugazhenthi, Effect of binder concentration on properties of low-cost fly ash-based tubular ceramic membrane and its application in separation of glycerol from biodiesel, J. Clean. Prod. 319 (2021) 128679.

[142] K.K. Katibi, et al., Strategies to enhance the membrane-based processing performance for fruit juice production: a review, Membranes 13 (7) (2023) 679.

[143] T. Arumugham, et al., Recent developments in porous ceramic membranes for wastewater treatment and desalination: a review, J. Environ. Manag. 293 (2021) 112925.

[144] B. Harman, et al., The use of iron oxide-coated ceramic membranes in removing natural organic matter and phenol from waters, Desalination 261 (1–2) (2010) 27–33.

[145] J. Radeva, et al., Hybrid ceramic membranes for the removal of pharmaceuticals from aqueous solutions, Membranes 11 (4) (2021) 280.

[146] X. Du, et al., A review on the mechanism, impacts and control methods of membrane fouling in MBR system, Membranes 10 (2) (2020) 24.

[147] N.N.R. Ahmad, et al., An overview of the modification strategies in developing antifouling nanofiltration membranes, Membranes 12 (12) (2022) 1276.

[148] D. Breite, et al., Particle adsorption on a polyether sulfone membrane: how electrostatic interactions dominate membrane fouling, RSC Adv. 6 (70) (2016) 65383–65391.

[149] T. Moritz, et al., Influence of the surface charge on the permeate flux in the dead-end filtration with ceramic membranes, Separ. Purif. Technol. 25 (1–3) (2001) 501–508.

[150] A. Tufail, W.E. Price, F.I. Hai, Impact of inorganic ions and organic matter on the removal of trace organic contaminants by combined direct contact membrane distillation–UV photolysis, Membranes 10 (12) (2020) 428.

[151] E. Alventosa-deLara, et al., Ultrafiltration ceramic membrane performance during the treatment of model solutions containing dye and salt, Separ. Purif. Technol. 129 (2014) 96–105.

[152] W.d. Melo, et al., Microfiltration of oil-in-water emulsion using modified ceramic membrane: surface properties, membrane resistance, critical flux, and cake behavior, Mater. Res. 25 (2021) e20210365.

[153] H. Chang, et al., A critical review of membrane wettability in membrane distillation from the perspective of interfacial interactions, Environ. Sci. Technol. 55 (3) (2020) 1395–1418.

[154] J. Usman, et al., An overview of superhydrophobic ceramic membrane surface modification for oil-water separation, J. Mater. Res. Technol. 12 (2021) 643–667.

[155] P. van den Brink, et al., Effect of temperature shocks on membrane fouling in membrane bioreactors, Water Res. 45 (15) (2011) 4491–4500.

[156] M. Simonič, Membrane surface properties and their effects on real waste oil-in-water emulsion ultrafiltration, WaterSA 45 (3) (2019) 367–373.

[157] M.T. Alresheedi, O.D. Basu, Interplay of water temperature and fouling during ceramic ultrafiltration for drinking water production, J. Environ. Chem. Eng. 8 (5) (2020) 104354.

[158] H. Choi, et al., Effect of permeate flux and tangential flow on membrane fouling for wastewater treatment, Separ. Purif. Technol. 45 (1) (2005) 68–78.

[159] D.M. Warsinger, et al., Scaling and fouling in membrane distillation for desalination applications: a review, Desalination 356 (2015) 294–313.

[160] C. Cai, et al., Ceramic membrane fouling mechanisms and control for water treatment, Front. Environ. Sci. Eng. 17 (10) (2023) 126.

[161] X. Luo, F. Deng, Nanomaterials for the Removal of Pollutants and Resource Reutilization, Elsevier, 2018.

[162] A. Basile, A. Cassano, N.K. Rastogi, Advances in Membrane Technologies for Water Treatment: Materials, Processes and Applications, Elsevier, 2015.

[163] Z. Bai, et al., Membrane fouling behaviors of ceramic hollow fiber microfiltration (MF) membranes by typical organic matters, Separ. Purif. Technol. 274 (2021) 118951.

[164] J. Huang, et al., Porous ceramic membranes from coal fly ash with addition of various pore-forming agents for oil-in-water emulsion separation, J. Environ. Chem. Eng. 11 (3) (2023) 109929.

[165] K. Gruskevica, L. Mezule, Cleaning methods for ceramic ultrafiltration membranes affected by organic fouling, Membranes 11 (2) (2021) 131.

[166] L.N. Nthunya, et al., Fouling, performance and cost analysis of membrane-based water desalination technologies: a critical review, J. Environ. Manag. 301 (2022) 113922.

[167] H. Sakamoto, et al., Intensive routine cleaning for mitigation of fouling in flat-sheet ceramic membranes used for drinking water production: unique characteristics of resulting foulants, Separ. Purif. Technol. 301 (2022) 121950.

[168] R.W. Baker, Membrane Technology, vol. 3, Encyclopedia of polymer science and technology, 2002.

[169] Y. Bao, et al., Pore-functionalized ceramic membrane with isotropically impregnated cobalt oxide for sulfamethoxazole degradation and membrane fouling elimination: synergistic effect between catalytic oxidation and membrane separation, Appl. Catal. B Environ. 254 (2019) 37–46.

[170] H.S. Erkan, N.B. Turan, G.Ö. Engin, Membrane bioreactors for wastewater treatment, in: Comprehensive Analytical Chemistry, Elsevier, 2018, pp. 151–200.

[171] M.A. Ahmed, S. Amin, A.A. Mohamed, Fouling in Reverse Osmosis Membranes: Monitoring, Characterization, Mitigation Strategies and Future Directions, Heliyon, 2023.

[172] W. Johns, Computer-Aided Chemical Engineering, Kirk-Othmer Encyclopedia of Chemical Technology, 2000.

[173] A. Zielińska, Methods for regeneration and storage of ceramic membranes, Acta Innovations (28) (2018) 72–81.

[174] X. Zuo, et al., Analysis of ceramic membrane fouling behavior and cleaning technology, in: E3S Web of Conferences, EDP Sciences, 2020.

[175] D. Vasanth, R. Uppaluri, G. Pugazhenthi, Influence of sintering temperature on the properties of porous ceramic support prepared by uniaxial dry compaction method using low-cost raw materials for membrane applications, Separ. Sci. Technol. 46 (8) (2011) 1241–1249.

[176] S. Tennison, K. Arnott, H. Richter, Carbon ceramic composite membranes for catalytic membrane reactor applications, Kinet. Catal. 48 (6) (2007) 864–876.

[177] S. Sarkar, et al., New clay–alumina porous capillary supports for filtration application, J. Membr. Sci. 392 (2012) 130–136.

[178] S.M. Samaei, S. Gato-Trinidad, A. Altaee, The application of pressure-driven ceramic membrane technology for the treatment of industrial wastewaters–A review, Separ. Purif. Technol. 200 (2018) 198–220.

[179] Y. Dong, et al., Cost and efficiency perspectives of ceramic membranes for water treatment, Water Res. 220 (2022) 118629.

[180] K.P. Goswami, G. Pugazhenthi, Treatment of starch-rich wastewater using fly ash-based low-cost tubular ceramic membrane, Environ. Prog. Sustain. Energy 41 (6) (2022) e13906.

[181] H. Chen, et al., Preparation and properties of coal ash ceramic membranes for water and heat recovery from flue gas, J. Chem. 2019 (2019) 1–10.

[182] N. Shao, et al., Defective analcime/geopolymer composite membrane derived from fly ash for ultrafast and highly efficient filtration of organic pollutants, J. Hazard Mater. 388 (2020) 121736.