Geopolymerization: a promising technique for membrane synthesis

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Abstract
Ceramic membranes are considered superior over their polymeric counterparts for applications at high temperature, pressure, and in aggressive environments with additional advantages of cleaning at high temperature. Preparation of porous ceramic membrane is expensive because the ceramic materials cannot be processed in a liquid state as polymers. Ceramic membrane synthesis involved solid powder preparation, consolidation, suspension formation, calcination, and sintering temperature which makes its synthesis very expensive. Geopolymerization is a heterogeneous reaction of aluminosilicate materials and chemical activators to form a three-dimensional structure having high mechanical strength without sintering. The overall percent energy and cost-saving of geopolymeric membranes were compared with conventional ceramic membranes. Recently, the geopolymerization technique has been used for membrane synthesis to replace conventional ceramic membrane synthesis. The objective of this review article is to discuss the potential opportunities and challenges in the synthesis and application of geopolymeric membranes.

1. Introduction

Membrane separation is a sustainable and preferred unit operation over other conventional technologies due to its cost-effective and efficient nature [1, 2]. Both inorganic and polymeric types of membrane materials play a prime role in the treatment of wastewater, gas separation, food, petrochemical industry, and other various applications [3]. Contrary to polymeric membranes, inorganic membranes are passive toward microbial growth and show superior physical and chemical properties in harsh environments and high thermal stresses [1, 2]. On the other hand, the inorganic membranes are expensive, as energy-intensive steps (solid powder preparation, consolidation, suspension formation, calcination, and high-temperature sintering) are involved in their preparation [3, 4]. Another reason for the high cost of the inorganic membrane is the requisite of luxurious raw materials such as zirconia, mullite, and titania in its synthesis, which has forced the researchers to search for sintering-free procedures and cheap raw materials owing to their reduced engineering cost besides being environmental benign [5]. Since last one decade, researchers are trying geopolymerization reaction engaging ashes and minerals as source materials to substitute exorbitant raw materials and heat-intensive steps for the fabrication of inorganic membranes [6, 7]. Comparison with other conventional practices, geopolymeric approach for the synthesis of inorganic membranes is both economical and eco-friendly [8–10]. Advantages of geopolymerization in comparison with other synthetic methodology include robustness and utilization of fly
ash as raw materials [11, 12]. Owing to the involvement of heat intensive steps it is challenging to adjust pore size, porosity and compressive strength in other synthetic routes [6].

In this review article, challenges like adjustment of pore size, porosity, and compressive strength besides opportunities namely sintering-free, eco-friendly, geopolymeric membrane synthesis, and its applications in different fields are discussed. Furthermore, a brief history of geopolymeric membranes, as well as the impact of source and alkaline materials ratios on their physical properties, is also discussed.

2. Scope of review

The motivation behind this is the costly synthesis of the porous ceramic membrane due to ceramic raw materials which like polymers cannot be processed in a liquid state. Ceramic membrane synthesis involves solid powder preparation, consolidation, and suspension formation, dispersion of particles in liquid for green casting, pressing, calcination, and sintering temperature, rendering its synthesis highly energy-intensive and costly. As already debated the geopolymerization is an economic sintering-free technique and so has attracted the attention of membrane researchers [13]. The term alkali-activated materials were first coined by J. Davidovits for the fire resistance inorganic polymers for construction purposes of green concrete and other applications. Later in 2006, the alkali-activated materials with low calcium oxide were coined as geopolymer [14, 15]. In 2005, Duxson et al. [9] reported that alkali bounded materials are porous and have the ability of fluid separation but at that time the technique was only used for the synthesis of concrete. Later in 2006, Rekik et al. [10] used kaolin for membrane synthesis with relatively high calcination temperature (1100 to 1250 °C) with irregular pore size and non-uniform porosity for microfiltration application. Since 2011, research has targeted the fundamentals of geopolymeric membrane such as selection of source materials, chemical activators, uniform pore size, porosity and compressive strength. Azimi et al. [16] reported in their review article that fly ash from thermal power plants possesses excellent physical and chemical properties with no external addition of silicate or aluminate sources for manufacturing geopolymeric materials. Bakri et al. [16] Summarized the synthetic parameters like source materials, chemical activators, the influence of sodium hydroxide, curing temperature, and characterization techniques of fly ash-derived geopolymeric materials. Zarina et al. [14] in their review article debated the use of different ashes as source material for geopolymerization originated from electric power plants relying on palm oil shells and palm oil bunches as burn material. Despite an increasing number of research articles on the synthesis of geopolymeric membranes, further effort is still needed for the controlled pore size, open porosity, and mechanical strength of the membranes. Figure 1 shows published research articles devoted to the synthesis of geopolymeric membranes for numerous applications.

3. Role of source materials and chemical activators

The key ingredients of geopolymeric materials are source materials that need to be dissolved in an alkaline medium to form a tetrahedral aluminosilicate porous substrate [3, 17]. The porous nature of geopolymeric materials serves as an interface between two phases that permit species of lower sizes and retain the particles of large size during separation processes [15, 18]. Fly ash, rice husk, bagasse ash, clay, and kaolin are aluminosilicate materials that are used as raw materials.
materials that are used as source materials in geopolymeric synthesis. Aluminosilicate minerals are those materials that are composed of an oxide of silicon, aluminum along other cations. Naveed et al\cite{13} transformed locally available kaolin to metakaolin (Si/Al = 3.0) with varying ratio of alkaline activators (3.3, 3.6, 3.8, 4.0, 4.1, 4.2, 4.3) with 18 M and ended up a geopolymeric membrane of 18 MPA for wastewater treatment. Zhang et al\cite{19} used metakaolin (Si/Al = 2.5) and sodium silicate (Na2SiO3/NaOH = 1.5) for the synthesis of faujasite geopolymeric membranes for the separation of alcohol and water mixture and achieved 185 kg m\(^{-2}\) h\(^{-1}\) water flux under operating pressure of 0.3 MPA. Moreover, another researcher [6, 8, 20] discovered that using rice husk ash necessitates the addition of aluminum sulfate for the ratio adjustment in the range of 2.0 to 3.0 for comparatively low compressive strength geopolymeric membrane. Dimas et al\cite{18} witnessed that using red mud (Si/Al = 2.5) residue of Bayer process during metallurgical treatment for making geopolymeric membrane in alkaline environment (Na2SiO3/NaOH = 2.5) is a promising technique for waste products utilization which is expected to combat environmental pollutants. Naveed et al\cite{6, 8}, investigation recommend the usage of fly ashes as aluminosilicate materials for the synthesis of geopolymeric membranes as red mud and metakaolin demand calcination before activation while fly ashes being calcination-free require no calcination temperature [21, 22]. It is pertinent to mention that most of the ashes contain heavy metals, which can be harmful in some applications like food applications, therefore acidic washing of ashes is suggested before such applications [23, 24]. In this research article [13], fly ashes (Si/Al = 2.5) of the thermal power plant are focused as a raw material for being free from external additives for Si/Al ratio adjustment for the fabrication of geopolymeric membranes for waste water treatment through microfiltration.

4. Pore size of geopolymeric membrane

The chief factor in membrane separation is pore size as it controls the passage of certain particles while retaining others [2, 25]. Lee et al\cite{26} reported that the size of the pores ranging from ∼20 Å to ∼1500 Å (0.15 μm) is characterized by N2 sorption method, while large pores couple mercury porosimetry as a viable option with a gas sorption technique to obtain porosity information in a large size range. Many researchers have used SEM visualization for pore size analysis by plotting the standard scale on the pore of membrane and averaging all pore sizes on a specific selected area [1, 20]. However, Mercury porosimetry is a standard tool for macropore structure analysis where the derived values of pore size and pore volume are repeatable to better than 1% standard deviation[23]. In polymeric membranes, the pore size is controlled by reaction parameters and rate of free-evaporation of the solvent molecule while in inorganic ceramic membranes the pore size is regulated by sintering temperature [27, 28]. In geopolymerization technique, the pore size is regulated by the curing temperature and addition of foaming agents [25, 29]. The curing temperature is a very important micro-structural factor in geopolymerization which enhanced the polymerization process and provides more compaction with the decrease in the pore size of the membrane [11, 30]Amir et al\cite{13}, found that the average pore size of geopolymeric membrane 1.04 μm was reduced to 0.8 μm after curing temperature of 90 °C for 15 h and preferred oven curing instead of steam curing. Khaled et al\cite{28}, found that curing time beyond 4 h improves the polymerization process resulting in compaction of geopolymeric membrane which significantly reduced the pore size. Bai et al\cite{31} investigated that the addition of foaming agent by direct method produced porous geopolymeric and obtained pores size of 0.01 μm using sunflower oil of 0.5% v/v as the foaming agent. Glad et al\cite{32} prepared a novel emulsion through templating method by adding alkoxysilanes as a cation in geopolymer paste and achieved porosity of higher than 70 volume % and pore size of 0.2–10 μm. Gul et al\cite{6} reported that hydrogen peroxide gives large pore size and porosity as compared to starch additives after force evaporation in geopolymeric paste during hydrothermal treatment and left micro–porous surface. Yan et al\cite{29} found that geopolymeric microsphere for absorption application using particle size distribution of 25 and 50 μm produced a pore size of ∼ 0.8 to 0.1 nm with BET surface area (39.74 and 37.30 m\(^{2}\) g\(^{-1}\)) due to silica and alumina dissolution. Other researchers [33–36] found that pore size characterization of geopolymeric membrane is significantly controlled by the amount of sodium hydroxide, a ratio of source material, pressing, and curing temperature. Generally, curing temperature is recommended for pore size regulation in the range of 60 to 70 °C, however, beyond this temperature curing has no significant effect on the pore size control.

5. The porosity of geopolymeric membrane

The porosity of the membrane is the volume of void spaces over the total volume of the membrane which offers permeation to permeate [6, 34]. Ge et al\cite{34} reported that porosity is the relative concentration of pore size which can be investigated through mercury injection apparatus while surface area through BET equations with N2 gas. The total porosity of the polymeric membrane is dependent on the nature of the solvent and solvent-polymer interaction, while in inorganic membrane the porosity is controlled through thermal treatment
[21, 31, 32, 37, 38]. In geopolymeric materials, the porosity of products can be regulated with the addition of foaming agents; however, an increase in porosity significantly reduced compressive strength [29, 30], Bai et al. [39], compared the effect of two foaming agents for the increase in the porosity of activated metakaolin geopolymeric paste. He found that the addition of 5% v/v egg white protein as a foaming agent enhanced the total porosity from 41.42 to 65% while the addition of the same amount of hydrogen peroxide enhanced the total porosity from about 74%. Naveed et al. [6] compared hydrogen peroxide and starch (10 v/v%) as a foaming agent in geopolymeric paste for enhancing the porosity from 29% to 37.33% and 51.09% respectively. Kaliappan [37] in his study used corn oil, starch, and waste palm as a foaming agent for the regulation of porosity from 26.6% to 42.21, 44.78 and 58.43% respectively and recommended hydrogen peroxide as a suitable foaming agent for enhancing porosity. Researchers [6, 15] found that the porosity, thermal conductance and compressive strength of geopolymeric membrane is related with the ratio of foaming agents because porosity reduced the interconnectivity which reduced thermal conductance. Generally, hydrogen peroxide as a foaming agent is recommended for enhancing porosity with no agglomeration formation and easy evaporation comparatively to other foaming agents which provides reasonable compressive strength [12, 30, 40].

6. Compressive strength of geopolymeric membrane

Compressive strength is important in pressure driven membrane because it shows behaviors of stability in micro and ultra-filtration when it is subjected to operation load and stresses [21]. Compressive strength of polymeric and inorganic membrane is controlled by the addition of organic and inorganic agents which help in strengthening the bond while compressive strength of geopolymeric membrane significantly depends on the influence of Na2SiO3/NaOH, Si/Al ratio, curing temperature, applied load during molding and addition of foaming agent [1, 38, 41]. Gul et al. achieved a maximum compressive strength of 62 MPa at 4.3% ratio of an alkali solution (Na2SiO3/NaOH) after a curing temperature of 90 °C for 14 h using metakaolin as source material, however, they applied about 46 MPa load on the paste [42]. However, Xu et al. [1], reported that compressive strength beyond 4.5% of Na2SiO3/NaOH did not increase due to a large number of silica monomers. Further, Amir et al. [6], recommended that metakaolin offers high compressive strength of 52 MPa due to its high Si/Al ratio as compared to other source materials such as fly ash, rice husk ash, and bagasse ash. Similarly, curing temperature in the range of 60 to 90 °C for 27 to 72 h increased 15% compressive strength of geopolymeric membrane. Some researchers [20, 41, 42] reported that compressive strength of geopolymeric membrane increased with the applied load during molding which decreases in the thickness of membrane which also affecting the resulting permeation as the porosity changes. Other researchers [6, 34] found that the ratio of foaming agents addition decreases the compressive strength due to pin holes and cracks after evaporation. Bhai et al. [34, 43] prepared a porous geopolymeric membrane of 61.23% porosity with the compressive strength 9.4 MPa for the removal of ammonium and copper ions from wastewater using direct foaming addition of 0.5% H2O2 and Tween 80 as surfactants. However, the typical observed compressive strength for geopolymeric membrane is in the range of 5 to 17 MPa for microfiltration and ultrafiltration applications which is easily achieved by curing temperature and complete dissolution of source materials in activators [1, 44, 45].

7. Cost comparison and energy saving of geopolymeric membrane with other conventional ceramic membranes

Cost analysis of membranes was estimated in the term of raw materials cost, electrical energy consumptions and other miscellaneous energy expenses [46]. Ceramic membranes have a high cost than polymeric membranes due to their expensive raw materials such as sodium carbonate, silica, alumina, zirconia, boric acid, calcium carbonate and kaolin etc and processing techniques of powder preparation, dispersion of solid particles in a liquid solution for the green cast, pressing, drying and sintering temperature [46, 47]. As the geopolymerization is a sintering-free technique and utilizes ashes as raw materials to produce a class of inorganic membrane called geopolymeric membrane has attracted the attention of membranologists to prepare low-cost membranes through this technique [22]. In the present work, In the present work, cost comparison of conventional ceramic membrane and geopolymeric membrane was done in terms of raw materials expenses and processing steps for 1 m2 with the thickness of 4 mm.

7.1. Cost saving
Geopolymerization is a heterogeneous chemical reaction of aluminosilicate with an alkaline activator which forms semi-crystalline material of tetrahedral network of silica and alumina [41]. Geopolymeric porous substrate of 1 m2 with the thickness of 4 mm was prepared using fly ash as a source material and chemical activators as a binder in the ratio of 2.5, while the ratio of chemical activators was kept 2.0 with 1% pore-forming
Table 1. Estimated calculations for the raw materials cost comparison and savings of geopolymeric and ceramic membrane.

| Raw materials for geopolymeric membrane | Mixing ratios (by weight) | Total cost GPM ($/m²) | Raw materials for ceramic membrane | Mixing ratios (by weight) | Total cost ceramic membrane ($/m²) |
|----------------------------------------|---------------------------|-----------------------|-----------------------------------|---------------------------|----------------------------------|
| Fly Ash/Chemical Activators ratio     | 2.5                       | —                     | Alumina/Binder                    | 2.5                       | —                                |
| Na₂SiO₃/NaOH ratio                    | 2.0                       | —                     | Binder (Boric acid, feldspar and sodium metasilicate) | 2.0                       | —                                |
| NaOH (grams)                          | 256                       | 0.097                 | Boric acid (grams)                | 2.92                      | 3.77                             |
| Na₂SiO₃ (grams)                       | 514                       | 0.0567                | Sodium metasilicate (grams)       | 0.12                      | 1.34                             |
| Fly Ash (grams)                       | 3526                      | 0.155                 | Alumina (grams)                   | 6.99                      | 104.85                           |
| H₂O₂ (ml) 1% by mass                  | 62.292                    | 9$kg                  | H₂O₂ (ml) 1% by mass               | 62.292                    | 9$kg                            |
| H₂O (ml)                               | 638                       | 1.99/l                | H₂O (ml)                           | 638                       | 1.99/l                           |
| Volume of Membrane (m³)               | 1 m × 1 m × .004 mm = 0.004 | —                     | Volume of Membrane (m³)            | 1m × 1 m × .004 mm = 0.004 | —                                |
| Total mass of GPM (grams)             | 4988                      | 2.37                  | Total mass of Ceramic paste (grams)| 707.283                   | 120.58                           |

| Type of Membrane | Cost consumption $/m² | Percentage savings |
|------------------|-----------------------|--------------------|
| Geopolymeric membrane | 2.37                | 98.03%             |
| Ceramic membrane  | 120.58                |                    |
agent as shown in table 1. The average cost of all the raw materials was obtained from different published sources for both geopolymeric and ceramic membrane [11, 14, 44, 45]. R. Meghnani et al [48] found that the overall synthesis cost of the ceramic membrane is due to expensive raw materials, mixing of precursor and thermal steps such as high calcination process, sintering temperature, hydrothermal, and curing treatment. Mittal et al, [43] prepared a low-cost ceramic-polymeric membrane using mineral clay, kaolin, and binding materials to reduce the overall energy of the membrane. Table 1 shows that the overall cost consumption for the synthesis of geopolymeric membrane was 2.37 $ m^{-2}$ and 82.71 $ m^{-2}$ for the ceramic membrane of 4 mm thickness. The overall saving based on raw materials is 98.03% per m².

### 7.2. Energy Saving

Membrane technology offers a cold filtration system that leaves heat treatment steps as in other conventional techniques of fluid treatment which leads to low operational expenditure (OPEX) and offers a better economy [49, 50]. In the synthesis of the ceramic membrane, the temperature is above 1000 °C while geopolymeric membrane is reaction-based synthesis and free of sintering [3, 51]. Hence, the enormous amount of thermal energy was saved and consequently reduced the overall cost. In the synthesis of the ceramic membrane, the temperature is above 1000 °C while geopolymeric membrane is reaction-based synthesis and free of sintering [47, 49, 52-54]. Hence, the enormous amount of thermal energy was saved and consequently reduced the overall cost. The thermal energy required for the sintering is calculated through equation (1).

\[
Q = mC_p T
\]

Where Q is the amount of sintering heat, \(C_p\) is the specific heat capacity in (kJ kg\(^{-1}\) °C), \(T\) is the temperature differences between sintering and atmosphere temperature [11, 47, 55]. The overall heat capacity of geopolymeric paste is composed of fly ash, sodium hydroxide, sodium silicate, water, and hydrogen peroxide are calculated by summation of all the raw materials as shown in table 2. The overall heat capacity of geopolymeric mixture was found using equation (2).

\[
C_p \text{ mixture} = \sum_{i} x_i C_{pi}
\]

Where the subscript ‘i’ denotes the specific raw material, superscript ‘n’ denotes the total number of raw materials in paste, \(C_{pi} = \text{Heat capacity of that specific raw material and } x_i = \text{mass fraction of that specific raw material. Heat required for hydrothermal treatment of } 1 \text{ m}^2 \text{ geopolymeric membrane at } 70 \text{ °C can be calculated by equation (1).}

\[
Q^* = 4988 \times 1.215 \times (70 - 25)
\]

\[
Q^* = 272.72 \text{ kJ per } m^2 \text{ of membrane with } 4 \text{ mm thickness}
\]

Similarly, the heat required in the sintering step was found 1579 kJ m\(^{-2}\) at 1100 °C for the synthesis of ceramic membrane. Table 2 shows that the overall energy consumption for the synthesis of geopolymeric membrane was 272.72 kJ m\(^{-2}\) and 1579 kJ m\(^{-2}\) for the ceramic membrane of 4 mm thickness. The overall energy saving based on raw materials is 82.71% per m². Youssef et al, [56] fellow the same procedure for economic analysis in the synthesis of geopolymeric and traditional bricks.

### 8. Separation performance of geopolymeric membrane

Separation kinetics of porous membrane is interlinked with porosity, pore size, the affinity of solvents, hydrophilicity, and hydrophobicity which control the flux and rejection of the feed solution [57]. The rapid
| Title                                                                 | Flux kg m\(^{-2}\)h | Applications           | Rejection % | Molarity (NaOH) | Filtration Area (cm\(^2\)) | Membrane thickness (mm) | Compressive strength (MPa) | References |
|---------------------------------------------------------------------|----------------------|------------------------|-------------|----------------|-----------------------------|-------------------------|---------------------------|------------|
| Synthesis and characterization of fly ash based geopolymeric membrane for produced water treatment (2019) | 29                   | Produced water         | 96          | 15 M           | 50 cm\(^2\)                 | 2                       | 18.5          | [58]       |
| Porosity control of self-supported geopolymeric membrane through hydrogen peroxide and starch additives (2019) | 66                   | Household wastewater   | 91          | 15 M           | 50 cm\(^2\)                 | 2                       | 13.05         | [6]        |
| Effect of sodium hydroxide and mould shape in geopolymer fabrication made with synthesised local clay for water filtration (2017). | 6.73                 | Waste water treatment  | 47 for colour, 88 for turbidity | 8 to 10 M | 72 cm\(^2\)                | 5                       | 3             | [59]       |
| Synthesis and characterization of inorganic membrane through geopolymerization (2017). | 20                   | Household waste water treatment | 90.1         | 15 M           | 50 cm\(^2\)                 | 10                      | 27            | [18]       |
| Synthesis of a self-supporting faujasite zeolite membrane using geopolymer gel for separation of alcohol/water mixture (2016). | 1.41                 | C\(_2\)H\(_2\)OH/H\(_2\)O mixture | 16.6 Alcohol composition of 70 wt%. | 14 M     | 63.31 m\(^2\)/g            | 10                      | 19.6         | [19]       |
| Inorganic Membranes: Preparation and Application for Water Treatment and Desalination (2016). | 2.1–1.9              | Household waste water treatment | 99.5         | 5 M            | 100 cm\(^2\)                | 10                      | 20            | [60]       |
| Preparation and characterization of a self-supporting inorganic membrane based on metakaolin-based geopolymers (2015). | 185                  | removal of Cu(II) from aqueous solution | 99.8         | 18 M           | 55 cm\(^2\)                 | 5.0                     | 16            | [1]        |
| Preparation of self-supporting NaA zeolite membranes using geopolymers (2013). | 0.42                 | Organic solvent dehydration processes | 99.5         | 10 M           | 80 cm\(^2\)                 | 9.4                     | 57            | [31]       |
| The hydrothermal transformation of solid geopolymers into zeolites (2012). | 2.67                 | Alcohol dehydration    | 90          | 15 M           | 140 cm\(^2\)                | 10                      | 49.1          | [56]       |
| New ceramic microfiltration membranes from mineral coal fly ash (2009). | 28                   | Water filtration       | 75          | 13 M           | 50 cm\(^2\)                 | 20                      | 4             | [61]       |
research on the synthesis of geopolymeric membrane is due to sintering-free synthesis and utilization of waste ashes as raw materials but limited applications is due to low flux as compared to other conventional membranes [26]. Geopolymeric membranes have been applied for wastewater treatment, ionic absorption, and alcohol/water mixture separation as shown in table 3.

9. Application of geopolymeric membranes

Geopolymeric membranes are used for wastewater treatment, produced water treatment and ethanol/water separation etc [36]. Various researchers [37] used metakaolin based self-supported geopolymeric membrane of 7 mm thickness with a total porosity of 62.64% for the removal of heavy metal, Nickel (II) ion through combined action of adsorption and rejection from industrial electroplating wastewater. The pore size and compressive strength were regulated through the molar ratio of H₂O/Na₂O. A significant increase in the flux was observed when the molar ratio of H₂O/Na₂O was increased from 18 to 21 and achieved the rejection of 97.3% with the permeate flux of 250 kgm⁻²h⁻¹ at Nickel (II) ion concentration of 300 mg l⁻¹. Xu et al., [1] used a metakaolin-based 5 mm thick geopolymeric membrane of 20 MPa strength with 18 molar ratio of H₂O/Na₂O for wastewater treatment and achieved flux of 185 kgm⁻²h⁻¹ with 100% rejection for nano-Al₂O₃ particles. In the very recent study of Xu et al., [38] metakaolin based geopolymer composite membrane was used for the treatment of pulp papermaking green liquor. The support layer was fabricated using foam material while the dense layer was prepared using dip-coating process without any foaming agent. A permeate flux of 245 kgm⁻²h⁻¹ was obtained for the removal of suspended solids from green liquor in the pulp papermaking. Papa et al., [39] used zeolite-based geopolymeric membrane of 2 mm thickness having a compressive strength of 3 MPa with a specific surface area of 211 m² g⁻¹ for improving the adsorption capacity of carbon dioxide over the 50% of the expected value (3.1%). Cui et al., [40] reported in their research work that metakaolin-based zeolite membrane is the considerable option for ethanol-water separation with the flux of 1.41 kg h.m⁻² and 16.8 separation factor. Yan et al., [41] reported that porous geopolymeric membrane has the potential for the removal of 99.9% solids particles in pre-treatment processes of wastewater treatment. He et al., [42] investigated that NaA zeolite membrane shows good rejection capacity for sodium ions up to 99.5% which is recommended for pre-treatment purpose in waste water treatment. Gul et al., [43] found that geopolymeric membrane is a good candidate for the removal of total dissolved solids in produced and household water with the rejection of 91.23%. However, the limited applications of geopolymeric membranes need the attentions of researcher to focus on the synthesis of geopolymeric membranes for forward osmosis and membrane distillation applications. There are also some challenges in its synthesis such as regulation of pore size, achieving uniform porosity, compressive strength, and low flux, which have a direct influence on the productivity of the processes [62–65].

10. Conclusions and future outlook

Geopolymerization is a sintering-free synthesis technique of inorganic membranes having many advantages and potential of waste ashes utilization as source material. The state-of-the-art review has focused on the source materials for the synthesis of geopolymeric membranes, the effect of various parameters on the pore size, porosity, and compressive strength. The application of geopolymeric membranes in the different separation processes has also been discussed in terms of flux and rejection. The sintering-free and easy fabrication procedure resulted in a low-cost inorganic membrane. The utilization of waste fly ashes as source material may further reduce the cost of production. However, extensive research is needed to understand the mechanism of pore size control, uniform porosity, and reasonable mechanical strength. The inert nature of geopolymeric membrane against harsh environments such as corrosive acid-base system needs to be further explored for various applications.

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Declaration of competing interest

All the authors in this research article declare that they have no personal relationships or approach that seems to influence the work reported in this article.
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