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A Mini Review on Advancements in Membrane Technologies for CO_2 Separation: The Role of Polyphenylene Sulfide Fillers

Afdhal Junaidi[a], Norazlianie Sazali[b,c], Triyanda Gunawan[a], Nurul Widiastuti[a]*

[a]Department of Chemistry, Faculty of Science and Data Analytics, Institut Teknologi Sepuluh Nopember, Sukolilo, Surabaya 60111, Indonesia
[b]Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia
[c]Centre of Excellence for Advanced Research in Fluid Flow (CARIFF), Universiti Malaysia Pahang Al-Sultan Abdullah, Lebuhraya Tun Razak, Gambang, Kuantan, Pahang, Malaysia

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ABSTRACT

Biogas is a renewable energy source mainly made up of methane (CH_4) and carbon dioxide (CO_2), demands excellent CO_2 separation with the goal to reach the minimum of 95% purity for CH_4 needed to produce biomethane. Pressure swing adsorption (PSA) and chemical absorption are the example of conventional techniques to remove CO_2 that have been commonly used, despite their limitations related to high energy consumption, operational complexity and efficiency. These limitations highlight the need for innovative and sustainable approaches to improve purification of biogas. This study explores the potential of using fillers based on polyphenylene sulfide (PPS) in polymeric membranes as a novel approach to enhance CO_2 separation from biogas. PPS makes a great option for membrane applications due to its aromatic polymer that is popularly known for its chemical resistance and thermal stability. Current developments, such as porous carbon-derived materials (PCs) and nitrogen-sulfur co-doped porous carbon (NSPCs), exhibit intriguing features for improving gas separation through their interactions with CO_2. The incorporation of PPS-based fillers into polysulfone (PSf) membranes is anticipated to further enhance CO_2 separation performance. This analysis highlighted significant advancements in membrane technology by comparing PPS-based systems with conventional techniques to demonstrate their benefits especially in terms of energy efficiency and simplified procedures. In addition, the review highlighted the current recent circumstances associated with material compatibility and scalability, which suggests future research areas. Development in this sector offers potential processes to completely transform the utilization of biogas by providing sustainable and efficient techniques for CO_2 separation, which would enhance the production of biomethane.

Keywords: Polyphenylene sulfide, biogas separation, membrane technologies

1.0 INTRODUCTION

In view of rising worldwide energy demands and the pressing needs for a shift to a renewable energy source, biogas has emerged as a highly promising alternatives given its ability to generate energy from organic waste materials [1–4]. This resulting in contributing to both waste management and energy generation. Biogas is mostly made up of methane (CH_4) and carbon dioxide (CO_2) offers a dual advantage, which it creates energy and reduces greenhouse gas emissions when it is fully utilized [2–7]. However, with the

* Corresponding to: Nurul Widiastuti (email: nurul_widiastuti@its.ac.id)
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goal to be effectively used as a fuel sources, biogas must be improved of having at least 95% of a methane content, in order to achieve high purity biomethane. This high purity is vital to meet the stringent standards for biomethane in a variety of applications, such as electricity generation, heating and as a vehicle fuel [8–10]. The important phase in the biomethane production process is the separation of CO_2 from biogas [9, 10]. Pressure swing adsorption (PSA) and chemical absorption are the example of traditional techniques to remove CO_2 that have been commonly used, despite their limitations [11–15]. Adsorption methods that are involved materials like zeolites, metal-organic frameworks and activated carbon, encounter challenges in terms of their regeneration cycles, adsorption techniques and overall effectiveness [16–20]. Extensive energy input to regenerate the adsorbents and maintaining their optimal performance are often required by these approaches, which resulting in higher operational costs and complexity. These significant issues are encountered similarly by the chemical absorption techniques that have been using solvents like amines to absorb CO_2 [15–18]. These techniques required solvent regeneration and involved in complex process controls which made it becomes energy-intensive, resulting in environmentally and financially burdensome. Consequently, CO_2 separation system growing a demand for a cost-effective, efficient and sustainable solutions.

During the past few years, membrane separation technologies offering the possibility of reducing energy consumption and simplified operation, which has emerged as an attractive alternative to traditional techniques [22–25]. In comparison with traditional method, semi-permeable barriers also known as membranes have capability to separate gases according to their solubility, size or diffusivity, offering an energy-efficient and more straightforward methods [22–25]. However, the efficacy of membrane technologies is frequently limited by intrinsic trade-offs between selectivity and permeability. In order to address these limitations, continuous research and development attempts have concentrated on improving membrane materials and introducing innovative fillers to increase separation efficiency [26–28]. A noteworthy development in this field is the utilisation of polyphenylene sulfide (PPS) as a based filler in polymeric membranes [29–31]. PPS is a type of aromatic polymer that popularly known for its exceptional thermal stability, mechanical strength and chemical resistance. Durability and tolerance to harsh operating conditions are crucial requirement during the membrane application, hence all those features made PPS as an appealing alternative [29–31].

The study conducted by X. Wang *et al*. (2017) on the fabrication of PPS membranes demonstrated that PPS exhibits high tensile strength and porosity [32]. An increase in porosity is generally accompanied by enhanced permeability and improved fluid flow rates [33]. Several studies have shown that the incorporation of small particles into membranes can effectively enhance membrane permeability [34]. Therefore, the use of PPS membrane materials to improve membrane performance under harsh conditions is highly desirable. Researchers are working to enhance the relationship between the membrane material and CO_2 by integrating PPS-based fillers into polymeric membrane, consequently enhancing the separation performance [35–36]. Membrane structure and properties can be modified in ways that increase CO_2 permeability while maintaining or even enhancing methane selectivity by designing the PPS-based fillers. This method utilizes the special chemical and physical qualities of PPS to produce membranes with enhanced functional features. There are multiple steps involved in synthesis and characterization of PPS-based fillers [35–37]. Pyrolysis and doping are including as a various process to synthesize porous carbon-derived (PCs) and nitrogen-sulfur co-doped porous carbon (NSPCs) fillers. Additionally, gas adsorption qualities and interaction with CO_2 can be enhanced by the development of these fillers [38–41]. The performance of these fillers is assessed through comprehensive enquiries of their efficacy on adsorption kinetics and thermodynamics, providing insight on how well they might improve CO_2 separation.

PPS-based fillers are combined into polysulfone (PSf) membranes once it is synthesized. PSf has a good mechanical properties and chemical resistance that are widely used for applications in membrane. Careful optimization of filler loading is important, in order to achieve the desired balance between CO_2 permeability and CH_4 selectivity during the integration of PPS-based fillers into PSf membranes [42–46]. Creating membranes that are both economically feasible for large-scale application and performing efficiently is essential for this optimization technique. A significant development in membrane technology represents by the integration of PPS-based fillers into polymeric membranes [36, 43–44]. These advanced membranes provide several advantages compared to conventional separation techniques. Advanced membranes have potential properties to simplify the separation procedures, enhance overall efficiency and decrease the energy consumption [29–31, 36–42]. In addition, silica and zeolites are an example of inorganic filler that encountered the compatibility issues and often faces obstacle related to integration into polymeric matrices and stability, which these issues can be addresses with utilization of organic fillers like PPS [17–20, 36].

The influence of these developments lengthens beyond the rapid utilization of biogas purification. PPS-based membranes engaged to the wider goal of improving the sustainability of renewable energy sources by enhancing the performance of CO_2 separation. Optimizing the benefits of biogas as a clean energy source and advanced membrane technologies development plays an important role in reaching this goal during the crucial production process of high purity biomethane. Moreover, the overall growth in the gas separation field, addressing long-standing obstacles, and opening-up new potential for upcoming study and development contributing by the development of membrane technology and material science.

2.0 LITERATURE REVIEW

2.1 Composition and Challenges of Biogas

Biogas is a byproduct of anaerobic digestion in an organic matter, that is important resources of renewable energy. It is primarily made up of CO_2 and CH_4, which methane is typically making up approximately about 55% and the remaining is constituting with 45% of carbon dioxide. Obtaining a methane concentration of at least 95% while minimizing the CO_2 content is the goal for upgrading to biomethane [1–3, 8–10].

The composition of biogas is influenced by the feedstock and digestion process, however in order of upgrading to biomethane, whilst the composition of biogas is influenced by the feedstock and digestion process. High purity biomethane is needed since it can be utilised as a clean energy source. However, the CO_2 content must be reduced significantly, in order to meet the high standards of quality for these uses. Therefore, a critical step during the upgrading process is the effectiveness of CO_2 separation from biogas.

Pressure swing adsorption (PSA), chemical absorption, and membrane separation are the example that includes in the conventional techniques for CO_2 removal. Each of these techniques come with their own benefits and limitations. Selective adsorption of CO_2 under high pressure is the basis of PSA, that utilizes the adsorption materials like activated carbon or zeolites. PSA encounters difficulty related to the capacity and regeneration of the adsorbents, although it can achieve high levels of purity. Frequent regeneration cycles are necessary, in order to maintain the performance that resulting in increasing of operational costs and energy consumption [11–15].

Amine is an example of solvents that has been used during the chemical absorption technique to capture CO_2 from biogas stream. These methods are effectively to reduce CO_2 levels and as well as energy-intensive regarding to the need of solvent regeneration. The regeneration process entails heating of solvent which requiring significant energy input, in order to release CO_2. In addition, chemical absorption processes required careful control to make sure the operation is efficiently, and solvent degradation is minimized due to the complex processes. These conventional techniques have their own limitations during the biogas upgrading that highlighted the needs of cost effective, sustainable solution of CO_2 separation and enhance the effectiveness. This resulting in broad interest for alternative technologies, which includes the separation of membrane that offers potential benefits in terms of minimize the process and energy efficiency [11–15].

2.2 Membrane Separation Technologies

Membrane separation technologies appeared as an attractive alternative for conventional techniques to remove CO_2. Membranes work as a selective barrier that permit certain gases went through based on their size, diffusivity or solubility variations while keeping others out. Compared to absorption and adsorption procedures, this separation system offers a simpler and renewable energy technique. Polysulfone (PSf) is a primary material for production of polymeric membranes, and it has substantial potential in application of gas separation. Good mechanical properties, thermal stability and chemical resistance are the characteristics that shows value in PSf membranes [42–46]. CO_2 removal from biogas is one of the examples of various separation procedures that are suitable for utilization due to these characteristics. Selectivity and permeability are two of the significant aspects generally described the performance of polymeric membranes [22–27].

Permeability can be rephrased as a rate at the point of a gas can pass through the membrane, while selectivity on the contrary can be defined as the capability to separate one gas from another preferentially. Ideally, biogas can be upgraded efficiently to biomethane if a membrane exhibits high permeability of CO_2 and high selectivity of CH_4. Nevertheless, there is obstacle to achieve high values for both parameters at the same time, due to the inherent trade-offs between selectivity and permeability. The continuing study has emphasised on enhancing membrane structures and materials to address these obstacles. The development of mixed-matrix membranes (MMM) that incorporate the polymeric matrices to inorganic fillers are one of the various approaches that have been discovered. MMMs have goals to improve the performance of membrane by utilising the strengths of both parts. In this case, gas selectivity and permeability can be enhanced by the integration of zeolites or metal-organic frameworks (MOFs) into polymeric matrices [38–44]. Even so, there are challenges regarding to the stability and compatibility of the filler materials with the polymer matrices that the techniques must face.

2.3 Polyphenylene Sulfide (PPS)-based Fillers

PPS is a type of aromatic polymer that popularly known for its exceptional thermal stability, mechanical strength and chemical resistance. Durability and tolerance to harsh operating conditions are crucial requirement during the membrane application, hence all those features made PPS as an appealing alternative. Current research is working on a novel approach between the integration of PPS-based fillers into polymeric membrane, consequently enhancing the separation performance [36, 43–44].

The ability to customize the interaction between membrane material and the gas being separated is the main advantage of PPS-based filler. Strong acid-base interactions and polarity differences are one of the unique characteristics exhibited by PPS that can affect the performance of separation. Researchers have a goal to improve the selectivity of membrane and permeability of CO_2 by integrating PPS-based fillers into polymeric membranes. The preparation of porous carbon-derived (PCs) and nitrogen-sulfur co-doped porous carbon (NSPCs) are the integration of PPS-based fillers that are typically involved. In addition, these fillers are intended increase gas adsorption qualities and CO_2 interaction [38–41]. Previous research by Kausar *et al.* demonstrated that combining poly(1-hexadecene-sulfone) with PPS resulted in CO_2 permeability of up to 177.3 Barrer [47]. Furthermore, CO_2 permeability reached 20.71 Barrer when integrated with PSf membranes, achieving CO_2/CH_4 selectivity of 9.11 [36]. Given the simplicity of the process and the promising results obtained, further straightforward development can enhance the performance of this material. As an example, porous carbon-based components can offer large surface areas and adsorption capability, while nitrogen-sulfur doping presents additional functional groups that improve CO_2 affinity. Moreover, improving the total separation effectiveness by raising the CO_2 selectivity and permeability is the use of these fillers in polymeric membranes that have been aimed during this research.

Careful optimization of filler loading, and membrane compositions are needed during the integration of PPS-based fillers into polysulfone (PSf) membranes. The aim is to approach a balance between CH_4 selectivity and CO_2 permeability while keeping up with the stability and performance of membrane. Research have demonstrated that the integration of PPS-based fillers is able to lead in notable progress compared to conventional polymeric membranes. As an illustration, PPS-based membranes indicated improvement of CO_2 effectiveness and decrease the energy consumption contrasted to traditional techniques [36].

Additionally, utilization of PPS-based filler resolves some of the problems regarding the compatibility related to inorganic filler, to improve the performance of separation. Silica and zeolites are an example of inorganic filler that encountered the compatibility issues and often faces obstacle related to integration into polymeric matrices and stability, which these issues can be addresses with utilization of organic fillers like PPS. Recent study has highlighted on understanding the system by which PPS-based fillers improved membrane performance. The effects of acid-base and polarity differences on separation of gas are one of the relationships between PPS and CO_2 that has been explored in in recent research. The goals of this studies are to clarify the fundamental ideas that take part to the enhanced performance of PPS-based membrane and lead to effective and sustainable technologies of membrane [36, 41–43].

3.0 STRATEGIES FOR INTEGRATING PPS-BASED FILLERS INTO MEMBRANES

A multi-faceted method encompassing the synthesis of high-performance fillers, their comprehensive properties, and subsequent incorporation into membrane system are the methodology that involved in improving CO_2 separation from biogas with the utilization of PPS-based. Firstly, the main part of this processes is the synthesis of porous carbon-derived (PCs) and nitrogen-sulfur co-doped porous carbon (NSPCs) fillers. In the synthesis of PCs, it is always started with the choosing of suitable carbon precursors, as an example is organic polymer or biomass that possess high carbon content. At a temperatures range between 800°C to 1000°C, the precursor materials undergo pyrolysis, which is a process where a thermal decomposition occurred in an inert atmosphere like argon or nitrogen. Organic components are decomposed by pyrolysis, resulting the porous carbon structures are left behind. The resulting material of porosity and surface area are vital to its filler like performance. Gases such as steam or CO_2 at high temperature is used in physical activation to offer additional pores, meanwhile, carbon material is treated with activating agents like potassium hydroxide and phosphoric acid involved in chemical activation which chemically alter the carbon and produce more porous structure. The carbon material is washed and dried to make the porous network stabilize during the post-activation, which resulting in a high-surface-area material that is fitting for applications of CO_2 separation.

3.1 Synthesis of PPS-based Fillers

The synthesis of NSPCs involved in introducing nitrogen and sulfur into porous carbon matrix to enhance the CO_2 adsorption. It is either throughout post-synthesis treatments or during the pyrolysis that this doping can occurs. During the direct doping method, carbon precursor is combined with the nitrogen and sulfur sources before pyrolysis nitrogen-rich polymers like polyimides and melamine is the typical nitrogen sources included, while thiophene and sulfur dioxide is the sulfur sources that may include in this doping approach. Nitrogen and sulfur are incorporated into carbon structure where the is mixture undergoes pyrolysis, resulting in improving its capability to communicate with CO_2 through the production of additional functional groups [47–51]. In addition, pre-pyrolyzed porous carbon is treated with nitrogen and sulfur-containing agent that involved during the doping of post-synthesis. This objective is using a technique, such as impregnation or chemical vapor deposition (CVD).

Diffusion and bonding of the agents to the carbon matrix are allowed by CVD that indicated the carbon material to vaporized doping agents at increased temperatures [52, 53]. Soaking the carbon material in a solution that includes the doping agents, then followed by drying and heat treatment to allow the integration of nitrogen and sulfur into the carbon structure is the processes that involved in impregnation. Additional functional groups that enhance the filler's interaction with CO_2 through acid-base interactions and polarity effects are introduced by these doping methods.

3.2 Characterization and Analysis

Analysis and characterization of PPS-based fillers are vital for examining their performance. In order to assess how well the fillers react to CO_2 and CH_4, gas adsorption studies are essential in this process. The volume of gas adsorbed are measured at various temperature and pressures during the volumetric adsorption methods, resulting data for generating adsorption isotherms. The adsorption capacity of the fillers is determined with the help of these isotherms. Gravimetric adsorption methods provide high-resolution details on adsorption kinetics and capacity, which these methods involve in measuring the weight differences of the fillers as they adsorb gas. In addition, understanding the dynamic behaviour of the fillers during separation of the gas needed these measurements. Pseudo-first order and pseudo-second order are an example of kinetic studies to examine the rate of adsorption, which explained the rate and predicted the performance. The analysis of thermodynamic offers perspectives on the energy changes connected to gas adsorption, which compute parameters like adsorption enthalpy and entropy from temperature-dependant data. The strength of interaction between gas molecules and the filler materials are comprehend with the help of these parameters.

Information on the morphology and surface characterizations of the fillers are examined by surface characterization methods that complements the studies of gas adsorption. Detailed images of the filler surface resulting in exposing overall appearance and pore structures are offered by the Scanning electron microscopy (SEM). Measuring the area and microporosity are vital for assessing the performance of fillers by the The Brunauer-Emmett-Teller (BET) method. These surface characterizations methods offer understanding of pore size allocation and surface area, which are vital factors in figuring the efficiency of the fillers for separation of CO_2.

3.3 Integration into Membranes

There are several important actions includes to improve the effectiveness of CO_2 separation in integration of PPS-based fillers into polymeric membranes. Initially, casting techniques are typically the first steps in the preparation of membranes, in which the techniques where a solution of polysulfone (PSf) and PPS-based fillers are prepared and cast onto support material to form a thin film. A solvent like N-methyl-2-pyrrolidone (NMP) is usually dissolved with the casting solution and spread evenly to attain the desired thickness of membrane [35–45]. After that, in order to solidify the structure of casting, membrane will undergo the process of drying and curing. Alternately, combining the PPS-based fillers with PSf polymer before membrane formation is the techniques that are involved in blending. Similar procedures to the casting technique are then applied to the combined mixture, where it is dissolved in a solvent and cast into a film. CO_2 permeability and CH_4 selectivity is carefully optimized by the concentration of fillers. Gas separation tests are included for the performance test of resulting membranes to measure their permeability and selectivity. The ratio of CO_2 permeability to CH_4 permeability is evaluated by selectivity, while permeability of CO_2 and CH_4 is involved in calculating the permeability of each gas through membrane. A vital step of filler loading optimization is obtaining the desired membrane performance. In order to identify the optimal loading for state of equilibrium in CO_2 permeability, membrane stability and CH_4 selectivity, the various filler concentration is examined. Additionally, the influence of varying filler concentrations on membrane characterization is examined by conducting the experimental trials. Prolonged examination under realistic operational circumstances to evaluate their durability and performance over time are subjected by membranes. For the purpose of ensuring the developed membranes can be produced efficiently and economically for industrial utilization, scalability is examined by analysing the continuity of membrane performance and the cost of manufacturing.

4.0 CHALLENGES, OPPORTUNITIES, AND FUTURE DIRECTION

4.1 Performance of PPS-based Fillers

Current technologies have brought attention to the significant influence of integrating PPS-based fillers for enhancing CO_2 separation effectiveness of biogas utilization in membrane technology. These fillers have effectiveness properties that are collectively involved to their performance in membrane system, which are strongly impacted by their structural characteristics, composition, and interaction with gas molecule. A unique benefits due to their inherent chemical and physical characterizations are provided by PPS-based fillers. Polyphenylene sulfide is an ideal prospect for utilization in tough separation environment due to its exceptional chemical resistance, thermal stability and mechanical strength. PPS-based fillers improved the process of separation by offering additional active sites for gas adsorption and enhancing the overall membrane material and gas molecule interactions during its incorporation into polymeric membranes.

Additionally, the co-doping assists to reduce the competitive adsorption of CH_4, as well as improving the CO_2 adsorption, resulting in improving the selectivity of membrane for CO_2. This state of equilibrium between developed CO_2 permeability and improving selectivity is vital for reaching the high purity biomethane, which is this condition is essential for obtaining the standards of biomethane [54–56]. Furthermore, the operational stability of the membranes is reflected by the performance of PPS-based fillers. The structural stability of PPS-based fillers has been discovered to be robust under different processes for operation, which maintaining their performance over long stretches of time. Membranes are subjected to real-world circumstances, including fluctuation in gas pressure and composition, which made this stability is crucial for practical uses. Steady separation efficiency throughout their operational life is offered by the lifespan of PPS-based fillers, which guarantee that the membranes to continue perform effectively [54–56]. In addition, PPS-based fillers provide to their superior performance because of their improved pore structures and increased surface area. More active sites for gas adsorption are provided by the increasing of surface area, which improve the overall effectiveness of separation [53–55]. Better gas transit and interaction are allowed by the optimized pore structure, which facilitated the total separation efficiency of CO_2 from biogas mixture. Better separation performance and higher CO_2 permeance are the results, compared to membranes without PPS-based fillers.

4.2 Comparison with Traditional Methods

A comparison of complex PPS-based membrane systems with traditional techniques such as chemical absorption and pressure swing adsorption (PSA) demonstrates numerous significant advantages when evaluating CO_2 separation technologies. In spite of they are firmly established and frequently utilized, traditional separation techniques face several challenges that influence their sustainability and effectiveness. To completely appreciate the advancements provided by PPS-based membrane system, it is vital to understand these challenges as well as the benefits the offer.

4.2.1 Pressure Swing Adsorption (PSA) and Chemical Absorption

There are two conventional techniques utilized for CO_2 separation, which are Pressure swing adsorption (PSA) and chemical absorption. PSA employs high and low pressure cycling to selectively adsorb CO_2 from a mixture of gases. The basis of this technique is adsorbent materials that absorb CO_2 at high pressure and release it during depressurization. PSA is effective at separating CO_2; however, the cycle of pressurization and depressurization requires a significant amount of energy inputs [54, 57]. Increased in operational cost and decreased in overall productivity might be influenced by this energy-intensive procedure. In addition, the operation process is further complicated by the necessity for the continuous maintenance of adsorbent material and regular regeneration.

Conversely, chemical absorption uses solvents, such as amines to absorb CO_2 from the gas mixture in a targeted manner. The CO_2 is then released for further processing or storage by heating the CO_2-loaded solvent to regenerate it. Despite of the effectiveness of chemical absorption in obtaining high CO_2 capture rates, it is also having its own limitations. Heating and solvent regeneration is necessity in this process; hence it contributes to high operating expenses due to the energy intensive [59, 60]. Moreover, the utilization of chemical solvents in absorption processes causes intricacy and environmental effects, which needed to be handled and disposed carefully.

4.2.2 Advantages of PPS-Based Membrane Systems

As opposed to conventional techniques, PPS-based membrane systems provide numerous benefits that resolve the limitations of PSA and chemical absorption. One of the main advantages of PPS-based membrane is their utilization on energy is reducing. Compared to PSA and chemical adsorption techniques, these membranes are created to separate CO_2 at lower pressures and temperatures [56–61]. This capability to perform under milder restriction results in lower energy consumptions, which van be drastically reducing the operational expenses and enhance the effectiveness of overall system.

The advantages of PPS-based membrane are further improved by their simplified operational procedures. In contrast to PSA, which requires intricate pressure cycling and chemical absorption, which solvent renewal is necessaries, PPS-based membranes work through simple permeation. The separation procedures depend on the differential permeation rates of CO_2 and CH_4 through the membrane material, without the requirements for significant pretreatment or regeneration. This simplicity is not only lowering the complexity of operating, but it helps to decrease total costs and minimizes maintenance requirements [56–61].

The enhanced adaptability of PPS-based membranes is a further significant benefit. PPS-based fillers are easily manufactured and incorporated into polymeric membranes utilizing scalable procedures that can be adjusted to fit various capacities and sizes. PPS-based membranes are easily implemented in various industrial applications and settings, due to their adaptability which made them an ideal choice for large-scale biogas upgrading initiatives. Their applicability and scalability are further enhanced by the ability to generate membranes at a lower cost and stable performance.

4.3 Challenges and Future Directions

Despite the significant strides made with PPS-based fillers in membrane technology, a numerous of critical issues must be resolved to fully optimize their utilization and their broad adoption can be attained. These issues encompass stability, scalability, compatibility of materials and as well as the necessities for further studies to improve and validate the development.

4.3.1 Scalability

Scalability remains as a major issue for the industrial utilization of PPS-based fillers. These fillers required to be synthesized and integrated into membranes by using processes that are both cost-effective and repeatable manufactured at a larger scale. Despite the promising recent development of laboratory-scale synthesis techniques, but it is not possibly transfer well to industrial-scale manufacturing. A careful consideration of consistency, cost and efficiency are required for the transition from small-scale studies to large-scale manufacturing. In order to achieve economic viability, the synthesis techniques have to be optimized to reduce costs and guarantee consistent quality of the PPS-based fillers are essential. The commercial success of PPS-based membrane systems relies on the development of scalable techniques that maintains the performance characteristics examined in laboratory environments [61–63].

4.3.2 Long-Term Stability

Another significant problem is ensuring the long-term stability of PPS-based fillers throughout various operational settings. Fluctuating temperatures, pressures and gas compositions are typically exposed by membrane systems, which influence the performance and durability of the fillers. In order to guarantee a consistent efficacy of PPS-based fillers over prolonged time frames, it is necessary to carry out comprehensive examinations of their stability under these circumstances. The main goal of the study should be comprehended to how environmental factors affect the effectiveness of structural integrity and performance in separation of the fillers. Research on long-term stability is useful in discovering potential problems regarding with degradation, fouling or changes in performance over time. The durability and reliability of PPS-based membranes in practical applications depends on how these problems are resolved [63, 64].

4.3.3 Material Compatibility

There are circumstance presents in the incorporation of PPS-based fillers, which is its compatibility with other materials, especially polymer matrices. In order to obtain the best membrane performance, PPS-based fillers must be blended with different polymers in a successful way. The mechanical properties, general performance and permeability of the membrane may be influenced by the interaction between polymer matrices and PPS fillers. Assuring that PPS-based fillers incorporated well with variety of polymers without degrading the performance of membrane is vital for broad adoption. Identifying ideal polymer matrices and creating strategies to improve the compatibility of PPS-based fillers should be the main highlighted of this study. This may entail experimenting various polymer formulations, optimizing processing parameters, and modifying fillers loading to obtain the desired qualities ofn performance.

4.3.4 Future Research Directions

Subsequent research ought to address these circumstances by focusing on numerous important domains. Firstly, it is vital to optimize the formulations of fillers, in order to enhance their stability and performance. This entails exploring with variety of doping schemes, adjusting filler compositions, and optimizing the manufacturing techniques. In addition, investigating substitute of polymeric matrices that that complemented PPS-based fillers may provide fresh opportunities for development of membrane technology. Through the discovery of polymers that enhance the compatibility and performance of PPS-based fillers, researchers can discover more membrane systems that work better. Development of novel synthesis methods for PPS-based fillers are also necessaries. Membrane performance can be substantially enhanced by developing new procedures for fillers with improved characteristics, such as increased surface area, functional groups and pore structures. Novel synthesis approaches to make it able in producing high-quality fillers with greater consistency and reducing cost should be explored by researchers.

4.3.5 Field Trials and Validation

Conducting thorough field experiments to validate the efficiency of PPS-based membranes in real-world biogas upgrading utilizations are another critical subject for future research. Despite the research conducted in laboratory provides insightful findings, environment of real-world frequently presents extra circumstances that must be resolved. Field testing will help in evaluating the practical performance of PPS-based-membranes throughout operating conditions, for example fluctuations in gas composition, temperature and pressure. Moreover, these trials yield valuable information on the long-term stability and durability of membranes, which aids in discovering any potential problems that may occur during the commercial applications.

5.0 CONCLUSION

Incorporated fillers based on PPS into polymeric membranes has emerged as an attractive promising approach for improving CO_2 separation from biogas. This technique is significantly improving the efficacy and efficiency of gas separation procedures by using unique characteristic of PPS and its fillers. Current development in the synthesis and utilization of PPS-based fillers presented their capability to improve permeability and selectivity of CO_2, which leads in enhancing performance of separation compared to conventional techniques. These advancements provide significant benefits in terms of reduced energy usage and simplified procedures, which contributing to economic viability and sustainability of biomethane production. The improved performance of PPS-based membranes contributes the broader objectives of renewable energy proposes through the facilitation of high-purity biomethane production, which is essential for meeting the biomethane requirements and promoting the utilization of biogas as an environmentally friendly power source. Nevertheless, numerous circumstances remain, such as issues regarding the compatibility of materials, long-term stability and scalability. Further study and development are necessary to address these circumstances and completely realize the potential of PPS-based membrane technologies. The development of this technology is depending on further research of optimization strategies, alternative polymeric matrices, and the scenarios of practical application. As a conclusion, biogas upgrading procedures may experienced a revolution if PPS-based membranes are implemented effectively. Resulting in adoption of sustainable energy sources and participating to more environmentally friendly energy landscape.

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CONFLICTS OF INTEREST

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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