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Review Article

An Overview of the Utilization of PET Plastic Bottle Waste for Membrane Fabrication

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Abstract

Plastic use, in this case including plastic drinking water bottles particularly polyethylene terephthalate (PET) has resulted in significant environmental, social, economic, and health repercussions. It will ultimately be deposited in landfills, requiring up to 1,000 years for each individual bottle to degrade. This review begins by briefly introducing the composition and characteristics of PET. It then details the methods for converting waste PET into valuable materials for diverse applications. The review emphasizes advanced uses of these materials in water treatment, highlighting the development of robust, organic solvent-resistant membranes. The primary aim of this review is to evaluate recent studies of PET bottle recycling to membrane technologies, membrane fabrication from PET waste, applications of PET-based membranes, advantages and challenges of using PET waste for membrane fabrication.

Keywords: Bottles; plastic; PET; recycling; waste

1. Introduction

Polyethylene terephthalate (PET) is a multifaceted, transparent, and lightweight substance extensively utilized throughout many industries, including food packaging, synthetic fibers, and beverage containers. Its superior mechanical strength, rigidity, and chemical resistance have rendered it a favoured option since the 1960s (Singh et al., 2019; Wang et al., 2015). The worldwide utilization of PET has markedly risen, resulting in its widespread application in the packaging of mineral water, soda, milk, and juice. Notwithstanding its advantages, the increase in PET production has led to a significant volume of waste, exacerbating environmental pollution (Dilara Hatinoglu and Dilek Sanin, 2022; Tian et al., 2023). PET trash, especially micro/nano plastics, is present in wastewater treatment facilities, signifying a considerable environmental issue (Tian et al., 2023).

PET, similar to other plastics, comprises organic polymers that exhibit slow biodegradability, presenting health and environmental hazards (Dyosiba et al., 2016). Studies have identified leached chemicals from PET, such as phthalates and bisphenols, prompting concerns over human health and environmental pollution (Jiang et al., 2020; Thoden van Velzen et al., 2020). The improper disposal of PET trash, a substantial component of global plastic waste, intensifies these problems (Pu et al., 2023).

Efficient management of plastic trash via recycling, energy recovery, and minimizing landfill utilization is crucial (Awoyera and Adesina, 2020). Nonetheless, existing methods like landfilling and incineration exhibit constraints and present environmental risks (Salem et al., 2008; Al-Salem et al., 2009), underscoring the necessity for improved waste management strategies.

The conversion of PET into recycled PET (rPET) by mechanical and chemical procedures provides a partial remedy to the waste issue. Mechanical recycling entails the sorting and cleansing of plastics, whilst chemical recycling decomposes PET into its monomers for subsequent repolymerization (Dutt and Soni, 2013). While rPET is typically utilized for inferior-quality items, enhancing the commercial value of recycled materials can elevate recycling rates. Investigating novel applications, such as the incorporation of recycled PET fibers in concrete, can increase the market for rPET and promote more sustainable practices (Siddique et al., 2008).

An effective strategy for addressing PET trash entails converting PET bottles into cost-effective membranes for water purification and energy generation. This addresses waste management while providing a sustainable and economical option for membrane manufacture (Sharma et al., 2021). In light of the global energy crisis and rising CO2 emissions, membrane technology offers a viable solution for sustainable energy production (Lycourghiotis, 2022). This review seeks to elucidate the technology, methodologies, and applications of utilizing PET waste in membrane production, emphasizing its potential to mitigate environmental and energy concerns.

Table 1. Characteristics of PET polymers.

Characteristics	Unit	References
Flexural modulus	2.4–3.1 (GPa)	(Ebewele, 2000)
Flexural strength	96.5–124.1 (MPa)	(Ebewele, 2000)
Glass transition temperature (T_g)	67–140 (◦C)	(Awaja and Pavel, 2005)
Impact strength	13.34–34.68 (J/m)	(Ebewele, 2000)
Intrinsic viscosity (IV)	0.7–0.85 (bottle grade) (dl/g) 0.4–2.0 (fiber grade) (dl/g)	(Ji, 2013)
Melting temperature	255–265 (◦C)	(Awaja and Pavel, 2005)
Tensile modulus	2.7–4.1 (GPa)	(Ebewele, 2000)
Tensile strength	58.6–72.4 (MPa)	(Ebewele, 2000)

2. Overview of PET Plastic Bottle Waste

PET is widely used because of its favorable chemical and physical properties. However, when PET trash is not properly managed, these characteristics can cause significant environmental problems. Understanding PET's structural makeup and qualities, the environmental effects of its disposal, and recycling procedures are critical factors in reducing plastic pollution.

2.1. Chemical Composition and Characteristics of PET

PET, a recyclable thermoplastic polymer, has received considerable global attention. It is a more environmentally friendly substitute for typical thermoplastics like polyethylene (PE) and other polymers. PET is a saturated polyester consisting of two main components: EG and dimethyl terephthalate (DMT), or EG and terephthalic acid (TPA). PET is widely utilized for its strength, clarity, exceptional thermal stability, and moldability (Han, 2019). Figure 1 depicts the chemical representation of the PET structure, with "n" denoting the number of repetition units. One of PET's most significant characteristics is its intrinsic viscosity (IV), which is influenced by the length of the polymer chain, which is regulated during polymerization (Li-Na, 2013). Table 1 provides an overview of PET's mechanical and physical characteristics. PET's mechanical properties are significantly influenced by its degree of crystallization, which is based on factors such as nucleating agents, degree of chain orientation, molecular weight, and so forth (Demirel et al., 2011).

PET is an aromatic polyester that has trouble degrading because it has non-hydrolyzable covalent connections with diethylene glycol terephthalate as a subunit substrate (Kawai et al., 2014). It is primarily synthesized from a combination of TPA or DMT with EG (De Vos et al., 2021). The three main processes in the manufacturing of PET are pre-polymerization, polymerization of bis(hydroxyethyl) terephthalate, and polycondensation (Awaja and Pavel, 2005).

PET is highly enriched in nature due to its widespread use, but it is typically regarded as an inert and "safe" plastic (Zimmermann et al., 2019). Its toxicity is typically linked to antimony leaching when exposed to heat (Wittkowski et al., 2019). Still, "phthalates" have been classified as hazardous substances and potential endocrine disruptors (Braun et al., 2013; Sax, 2010).

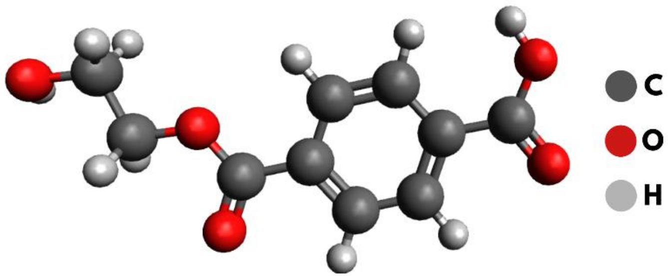

Figure 1. Chemical structure of PET

2.2. Environmental Impact of PET Waste

Despite the numerous advantages of PET, its environmental profile provides a significant challenge, mostly due to its resistance to biodegradation. Once discarded, PET does not decompose quickly in natural environments. Water used for drinking or groundwater is becoming polluted by PET plastic and its leachate. Certain investigations have recorded the transference of microplastics from PET plastic into water. Research on groundwater in north-western Germany revealed an average concentration of 0.7 microplastic particles/m^3 (Mintenig et al., 2019). Besides polluting groundwater, all types of plastics eventually accumulate in the oceans, where they gradually break down into microplastics or nanoplastics. These tiny plastic particles, along with their associated plasticizers, are readily ingested by various organisms. Microplastics and plasticizers pose a significant risk to zooplankton and potentially to organisms higher up the food chain (Vered et al., 2019).

Nanosized PET plastic particles have raised significant concerns over potential environmental and human health risks. Nanoplastic exposure to Humans may be exposed through oral inhalation, ingestion, or dermal absorption due to the utilization of plastic items (Prata, 2018). Plastic nanoparticles are anticipated to have a primary entry pathway, as they can be ingested through the consumption of fish or contaminated water. Conversely, plastic ingestion in humans may occur through intentional swallowing, leading to the most adverse outcome: gastrointestinal blockage, psychiatric disorders, allergies, asthma, and chronic pneumonia (Yaka et al., 2015). Nanoplastic accumulation in fish has also been shown to impair their aggregative behavior and foraging activities. Augmented nanoplastic concentrations disturb metabolic processes by increasing ethanol, lysine, and adenosine levels in fish livers (Crossman et al., 2020).

2.3. Current Recycling Methods of PET

The utilization of PET from plastic waste is being widely practiced in the world today. As plastic waste management becomes more important, more companies are using it as a substitute raw material to lessen their negative effects on the environment (Mohan et al., 2021; Siddique et al., 2008). There are many types of utilization that can be done. The recycling of PET is essential component of the circular economy, which tries to save resources and cut down on waste. The demand for PET is predicted to rise in a few years due to the continual development of novel methods and uses. In order to achieve a sustainable future, PET recycling technologies must be developed and optimized (Muringayil Joseph et al., 2024).

The incorporation of discarded plastic into asphalt pavements is one such application. The viability of producing beneficial additions from waste plastics has been examined in a number of previous studies, including PE (Liang et al., 2021; Wang et al., 2022), PET (Li et al., 2021; Xu et al., 2021), and polypropylene (PP) (Xu et al., 2022). The performance of asphalt mixtures was assessed using tests such as the indirect tensile stiffness modulus, moisture susceptibility, and immersion Hamburg wheel-tracking. Findings revealed that PET-TETA is a semicrystalline material containing around 26% hydration water, which can be gradually released during asphalt pavement production. As a result, PET-TETA is expected to function as a sustainable and effective additive for Warm Mix Asphalt (WMA), offering a practical approach to addressing plastic waste disposal challenges (Zou et al., 2024).

The findings reported that mortar made from recycled PET with constantly graded sand was stronger than mortar made from single-sized gradation (Ge et al., 2013). The flexural and compressive strengths using recycled PET mortar improved by increasing sand-to-PET proportion. The production of compact concrete using fine aggregate derived from rPET packages. The strength at compression of the 28-day waste PET lightweight aggregates (WPLA) concrete decreased by 5%, 15%, and 30% compared to the control concrete, as its WPLA content rose by 25%, 50%, and 75%, respectively. The concrete containing 25% WPLA exhibited superior durability (compressive strength-to-density relation) compared to the control concrete (Choi et al., 2009).

An energy-efficient phase inversion approach is employed to fabricate a composite oil sorbent using carbonaceous waste residual from the gasification of oil refinery bottoms and used PET bottles (Mitra et al., 2021). The composite has a promising future in the treatment of industrial oily wastewater because it can effectively extract oil from mineral or paraffin oil-in-water emulsions through sorption, with an efficacy of > 99.7%.

PET waste's 11% carbon fixed content, little ash and impurities content, and roughly 30% oxygen concentration make it a viable Feedstock for the synthesis of CO_2 and other nanoporous carbons. Nonetheless, transformation into carbonaceous sorbents by conventional methods seems impracticable due to competing recycling technologies and limited yield. While having comparable total carbon contents, various polymeric wastes including PVC, PP, and HDPE are less suited than PET because of their lower fixed carbon contents (Sharifian and Asasian-Kolur, 2022).

Inexpensive porous carbons were made from old PET plastic bottles, and their ability to absorb CO_2 was examined. In order to create porous carbons, PET bottles underwent carbonization and activation using NaOH or KOH. The produced carbons textural characteristics were significantly affected by changing the activation temperature. Furthermore, porous carbons derived from PET demonstrated significant CO_2 uptake, high selectivity for CO_2 over N_2 and CO, ease of regeneration, outstanding cycle stability, and fast adsorption and desorption rates for CO_2 (Yuan et al., 2020b). The ability of the produced porous carbons to capture CF_4, a greenhouse gas with a high global warming potential, was also evaluated. These PET-based porous carbons possess advantageous properties for practical CF_4 capture, including high CF_4 absorption capacity, excellent CF_4/N_2 selectivity at relatively low CF_4 pressures, ease of regeneration, rapid adsorption/desorption kinetics, and remarkable recyclability (Yuan et al., 2020a).

Plastic trash bottles were dissolved in phenol to enable cracking reactions and catalytic steam reforming that generate hydrogen and liquid gasoline (Nabgan et al., 2021). The impregnation method achieved a phenol transformation of 72.8% and a hydrogen yield of 56% at about 700 °C during the catalytic reaction; these figures increased to 83.8% and 76%, respectively, following hydrothermal treatment. PET breaking and phenol reforming using steam reactions produced useful components as dibenzofuran, 2-methyl phenol, and benzene, as demonstrated by the analysis of liquid products acquired via GCMS (gas chromatography mass spectrometry).

Utilizing waste PET plastic, large surface area nitrogen enriched mesoporous carbon (N-MC) was created utilizing in a financially viable method utilizing MOF-5 assembly. The most sensible method for recycling PET waste is to use one or more chemical routes, which depolymerize PET and yield 1,4-benzendicarboxylic acid, it is subsequently employed as an intermediate linkage to synthesize MOF-5. Super-capacitors demonstrated exceptional electrochemical and energy storage performance when evaluated in a three-electrode setup with 6 M KOH as the electrolyte. After 400 segments, the GCD stability test yielded retention of approximately 98%. N-MC is a promising alternative for restoration of the environment and as a cost-effective electrode material for supercapacitor use due to its composition from waste PET plastic (Ubaidullah et al., 2021).

A study highlighted the efficiency of a low-cost electrocatalyst in batch-scale electro-Fenton (EF) processes for decomposing salicylic acid (SA) in effluents produced by the MIL-53(Fe)-metal-organic framework (MOF) Fe_3O_4@C (MIL-53(Fe)@Fe_3O_4@C) (Priyadarshini et al., 2023). The electrocatalyst was synthesized by combining iron scrap waste and PET. Another study, demonstrated the use of MIL-101(Cr)/ED as an adsorbent for the effective removal of Pd(II) ions from wastewater. This adsorbent, created from discarded PET bottles and functionalized with ethylenediamine (ED), achieved over 80% Pd(II) ion removal even in the presence of competing ions, highlighting its strong affinity for Pd(II) (Maponya et al., 2023).

Benzene-1,4-dicarboxylic acid (BDC), one of the monomers of PET, can be used to create extremely effective energy storage materials. Therefore, it would be wise to recover BDC from PET waste in order to recycle waste and help the economy while protecting the environment. Rather than using alternative polymers as a precursor to the creation of metal-organic frameworks (MOFs), PET bottles were used to generate BDC for supercapacitor use (Xu et al., 2019; Zhu et al., 2019). As is well acknowledged, materials based on metal oxides are essential for energy applications (Ahmad et al., 2017; Ahmed et al., 2019; Yang et al., 2019; Yi et al., 2019).

In order to synthesize graphene from PET bottles waste, (Ezzat and Ali, 2022) looks into the possibilities of employing it as an active material that can be used at a low cost for the removal of methylene blue and methyl orange from water solutions. The synthesis process was carried out in an environmentally friendly manner by producing stainless steel in an autoclave that speeds up the pyrolysis process and lowers the emission of harmful gasses. Numerous variables, including contact time, the solution's starting pH, agitation speed, beginning concentration, and sorbent dosage, were examined in relation to the percentage of dyes removed. The experimental results demonstrated that the synthesized graphene effectively acts as a reactive material for removing dyes from aqueous solutions.

A previous study introduced innovative PET aerogel composites derived from recovered PET fibers sourced from plastic bottles, marking its effective development for the first time (Goh et al., 2023). Using ethyl cyanoacrylate adhesive, PET sheets are layered to create honeycomb shapes with different cell sizes. The proposed PACs (PET aerogel composites) outperform commonly available commercial goods and aramid honeycomb-reinforced silica aerogel composites. They might be suitable substitutes for cold chain applications and building insulation.

Many polymer matrix composites use rPET as the matrix material. Recycled PET degrades during recycling, giving it a lower molecular weight and worse mechanical qualities than virgin PET. By combining rPET with vPET, polyamide, which is polycarbonate, which chain extenders, etc. and using compatibilizer to enhance the interfacial phenomenon and create strong links, it is possible to offset the mechanical performance loss of rPET. The tensile characteristics were significantly improved by mixing rPET with polypropylene. Polylactic acid was added to rPET, which simultaneously decreased its mechanical qualities and enhanced its degradability. Blending rPET with chain extender, PE, polypropylene, polycarbonate, polyamide, etc., among other features, enhances the blend's characteristics while minimizing environmental waste, thereby preventing the spread of pollutants (Singh et al., 2021).

Another researcher employed phase-transfer catalyzed alkaline hydrolysis with ultrasound assistance to successfully extract terephthalic acid (H_2BDC) from trash PET bottles under mild circumstances (Jung et al., 2020). The ideal conditions for achieving a recovery rate of 99.91–100% of H2BDC included a duration of 1.5 hours, a temperature of 83.2°C, and a NaOH concentration of 14.5%. A porous magnetic carbon composite (α-Fe/Fe3C) was synthesized using high-purity H2BDC, derived as an organic ligand from an iron-based MOF. This material's capability to adsorb and extract TCH from aqueous solutions was evaluated. The exceptional reusability and magnetic separability of the α-Fe/Fe3C composite highlight its significant potential for treating wastewater contaminated with antibiotics.

Recycling and PET bioconversion may be made possible by active PET biocatalysts. Thus, there is a pressing need to create novel approaches that can improve these PET biocatalysts' solubility, productivity, stability, and catalytic activity in challenging environments including high pH and salt. The use of bioengineering techniques to increase the robustness and catalytic behavior of PET biocatalysts has gained significant interest consequently (Samak et al., 2020).

The reclamation of PET waste using chemical catalysis is a workable, economical, and sustainable "waste-to-wealth" approach. Employing appropriate catalysts improves the distribution, selectivity, and yield of commercially valuable products while simultaneously reducing the total energy usage and reaction duration of the process. This advancement supports the modernization and optimization of industrial production technologies in a positive way (Jiang et al., 2024).

PET bottled waste was used as material for creating solid-state fluorescent Carbonized polymer dots (CPDs) from PET bottle trash in a single synthetic step (Prasetya Aji et al., 2023). The temperature and length of time have a significant impact on the photoluminescence (PL) characteristics of the solid-state PET-CPDs made by heating. The synthesis temperature was established in this work using the PET's thermal breakdown (melting point), and it is possible to investigate how this temperature affects the PL characteristics of PET-CPDs. The findings suggest that the development of the conjugated aromatic core of CPDs significantly depends on PET melting point.

Other study devised a low-cost, environmentally friendly method of producing fluorescent carbon dots (CDs) from waste PET by aerial oxidation and hydrothermal processing in an aqueous hydrogen peroxide solution. The synthetic procedure didn't require any costly, hazardous, or corrosive reagents, nor did it call for harsh circumstances. The resulting CDs had a lot of oxygenous groups and special PL characteristics. These characteristics allowed the very accurate and selective detection of ferric ions (Fe^{3+}) by an on-off PL quenching effect. Good results were obtained by the sensing device for the Fe^{3+} and PPi tests in authentic samples of water and human urine (Hu et al., 2019).

To depolymerize PET bottles, Zhou et al. (Zhou et al., 2017) collected and cleaned the bottles before subjecting them to glycolysis with neopentyl glycol and dipropylene glycol (DPG) in the presence of an N-butyl titanate catalyst. The glycolyzed oligoesters, a byproduct of this straightforward and eco-friendly depolymerization process, were used to create innovative waterborne polyurethane dispersions (PUDs). These oligoesters were incorporated into both the hard and soft segments of the polyurethanes. The resulting aqueous polyurethane dispersions, with an optimal balance of hard and soft segments, demonstrated superior performance in formulations where the glycolyzed oligoesters were integrated into the hard segment regions.

3. Membrane Fabrication from PET Waste

One promising strategy for decreasing plastic waste and enhancing resource efficiency is to use discarded plastics, particularly PET into the membrane manufacturing process. Non-biodegradable waste plastics, such as PET bottles, cause significant environmental problems because they collect in landfills and oceans. The use of these plastics for membrane production not only makes it easier to manage plastic waste, but it also helps to generate useful materials for a variety of uses.

3.1. Basic Principles of Membrane Fabrication

Membrane technology is an engineering processes used to transport or reject chemicals, components, and species across membranes. The membrane is a selected barriers that allows certain molecules or ions to traverse while excluding others. Membrane-based separation technologies are widely acknowledged as a highly promising method to tackle the global ecological problems of contamination of water and usage (Istirokhatun et al., 2021; Susanto et al., 2019a). PET membranes have garnered a lot of attention in chemical separation and pollution focus on chemical separation and environmental contamination management because of its strong mechanical qualities and great chemical stability (Chen et al., 2023). PET is one of the substances utilized in the production of mineral water bottles. Conversely, garbage generated by plastic bottles has the ability to create thin layers or films, which is known as membranes (Korolkov et al., 2018).

Membranes can be fabricated using various techniques, including interfacial polymerization, sputtering, solution casting, extrusion, melt pressing, and phase inversion. The most often utilized procedures for fabricating polymeric membranes are phase inversion (Figure 2) and electrospinning. The technology chosen is determined by the manufactured membrane's efficiency, characteristics, and cost of fabrication (Tan and Rodrigue, 2019; Xu' and Agrawal', 1996).

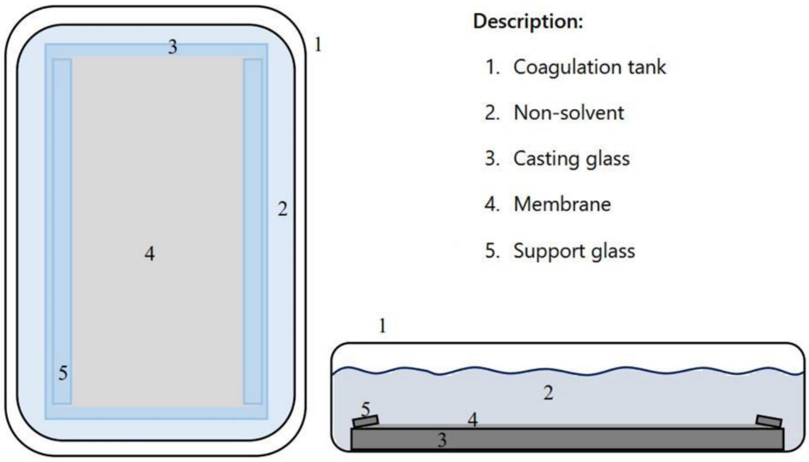

Figure 2. Fabrication of polymeric membranes via phase inversion

3.2. Methods of PET Conversion into Membrane Material

The phase inversion method involves transitioning a polymer from its solid form to a solution or molten state under carefully controlled conditions, highlighting the significance of optimizing membrane fabrication parameters. This process is mainly influenced by thermodynamic and kinetic factors. During phase inversion, phase separation occurs, dividing the material into polymer-rich and polymer-lean regions. The polymer-rich region solidifies through processes such as gelation, vitrification, or crystallization, creating the solid membrane structure, while the polymer-lean region forms pores in the final membrane. Phase separation can be initiated using methods like immersion precipitation, controlled evaporation, thermal precipitation, or vapor-phase precipitation, with immersion precipitation being the most commonly employed technique (Hołda and Vankelecom, 2015).

The prior study by (Tamam Ibnu Ali et al., 2023) underpins the production of PET membranes from recycled bottles. Waste from PET plastic bottles was dissolved in phenol solvent to create Solution A, which was then homogenized for three to four hours at 100^0 Celsius using a magnetic stirrer. Solution B was created in a different container by homogenizing Pebax for two to three hours at 100 degrees Celsius after dissolving it in phenol in the same amount as solution A. Ultimately, zeolite was dispersed in phenolic solvent and homogenized for three to four hours at 125 ^{0}Celsius to create solution C. For A, B, and C, the phenol solvent ratios utilized in each solution were 2:2:1. Solution B was combined with solution A after each solution had been homogenized, and then solution C was added. An hour was spent on the homogenization process's last phase for optimal results.

After stirring the uniform dopant solution, it was permitted to remain stationary to eliminate bubbles prior to being placed onto a glass plate with tapered edges to regulate the membrane's thickness. Submerged in a bath for coagulation containing water and ethanol in a 1:15 ratio to facilitate diverse phase transitions procedures (Tamam Ibnu Ali et al., 2023). Other research by (Bhuyan et al., 2023) also made PET membrane with cellulose nanofibers addition from waste paper. It can be employed to make the membranes hydrophilic.

Alongside the phase inversion method, electrospinning is another commonly utilized technique for membrane fabrication, particularly for creating porous membranes used in filtration and desalination applications (Efome et al., 2016). This process uses electrostatic forces to produce polymer films with a high surface area. According to (Rafiei et al., 2013), electrospinning operates by generating strong mutual repulsive forces that counterbalance the weaker surface tension of the polymer solution. Conducted under atmospheric conditions, the process involves filling a capillary tube with the polymer solution. Surface tension maintains the solution's cohesion, while an applied electric field charges the solution's surface. When the electric charge exceeds a critical level, the electrical forces overcome the surface tension, causing the solvent to evaporate. This allows the polymer to solidify, forming fibers at the capillary tip and depositing them onto a collection substrate.

3.3. Characteristics of Membranes Fabricated from PET Waste

PET waste membranes have a distinct set of physical, chemical, mechanical qualities render them suitable for diverse applications, especially in filtration and environmental control. The membranes can be customized with specific pore sizes and surface morphologies to meet particular filtration objectives (Susanto et al., 2019c).

Membranes made from unmodified PET showed inadequate mechanical properties. However, the addition of higher molecular weight polyethylene glycol (PEG) considerably enhanced both permeation flux and structural stability. Recycled PET served as the base polymer, and solvents like phenol, m-cresol, or dimethyl sulfoxide were utilized to create UF membranes through the phase inversion method (Kusumocahyo et al., 2020). Studies revealed that lowering the polarity of the nonsolvent improved water permeability, while increasing the concentration and molecular weight of additives in the casting solution boosted the membrane's flow performance.

Finally, membranes made from PET waste not only promote sustainable waste management, but also provide feasible solutions for a variety of filtration and separation needs. These membranes can be precisely adjusted for specific industrial usage using engineering procedures and chemical modifications without compromising their structural and functional integrity.

4. Applications of PET Waste-based Membranes

Recent research has emphasized converting PET waste into high-value products (Bian et al., 2024). The growing environmental concern about plastic waste has encouraged the exploration of sustainable alternatives, including the exploitation of PET waste in membrane technology. Both environmental sustainability and economic advantages can be attained with the appropriate application of these materials. PET-based materials and their conversion process are explored in this section along with their uses in membrane technology such as pressurized filtration membrane, concentration diffusion (RO), and gas separation.

4.1. Pressurized filtration membrane

Membrane filtration (MF) is a pressure-driven technique that uses a membrane to filter particles both mechanically and chemically. Membranes are typically produced using the phase inversion or phase separation method, where a uniform polymer solution undergoes precipitation, dividing into a polymer-rich solid phase and a polymer-lean liquid phase. The membrane is created by either casting the polymer solution into a film on a substrate or through spinning (Susanto et al., 2020). Membrane filtration is crucial for water and wastewater treatment, providing greater efficiency and cost-effectiveness compared to conventional water treatment methods. These membranes, acting as microporous barriers, are categorized based on their average pore size into four types: reverse osmosis (RO), ultrafiltration (UF), microfiltration (MF), and nanofiltration (NF). Their separation ranges are as follows: MF: 100–1000 nm, UF: 5–100 nm, NF: 1–5 nm, and RO: 0.1–1 nm (Iorhemen et al., 2016).

Among other conventional approaches, membrane filtration is the technology that is most often used for treating industrial effluents (Chen et al., 2017; Quist-Jensen et al., 2017). This approach is more practical and efficient since it produces less waste and uses less energy (Moeinzadeh et al., 2019). These methods have already been applied for extracting heavy metals from contaminated water sources (Huang et al., 2021; Roy et al., 2021). The addition of inorganic compounds to mixed matrix membranes provides several advantages, including a high zeta potential, excellent selectivity, and improved surface wettability or hydrophilicity (Dechnik et al., 2017; Mondal et al., 2017).

Recycling PET bottles can result in membrane-forming polymers, which addresses environmental concerns and transforms waste into more valuable products. Traditionally, easily accessible materials like polysulfone and polyvinylidene fluoride have been utilized to create ultrafiltration (UF) membranes. Ultrafiltration (UF) membrane separation lies between nanofiltration (NF) and microfiltration (MF), with both UF and MF membranes being porous. UF membranes often possess an asymmetric structure characterized by a significantly denser skin layer, leading to diminished pore size and lower surface porosity, hence augmenting hydrodynamic resistance (Singh and Hankins, 2016).

Research is currently investigated the potential of using PET plastic bottles as an alternative to synthetic polymers derived from fossil fuels (Hut et al., 2024). PET membranes have consistently proven suitable for membrane production due to their properties, such as recyclability, resistance to solvents and chemicals, outstanding selectivity, and the ability to achieve high flow rates (Khashij et al., 2022). Ultrafiltration membranes have shown over 99% effectiveness in removing common algal cells, suspended solids, and other large organic and inorganic particles, ensuring efficient removal of particulates and microorganisms (Imdad and Dohare, 2023). Additionally, ultrafiltration is recognized as a promising approach for eliminating bacterial contaminants. Studies suggest that incorporating TiO_2 at a concentration of 3wt% can effectively enhance the antibacterial and antifouling performance of membranes (Susanto et al., 2019b).

Waste plastic bottles hold significant potential as cost-effective, sustainable, and environmentally friendly materials for membrane production. Utilizing the immersion-precipitation phase inversion technique, a PET-B membrane was fabricated from recycled PET plastic bottles. The properties of the membrane were further enhanced by incorporating LiCl as an additive. This modification improved the hydrophilicity, porosity, and selectivity of the membrane, which initially demonstrated high permeability but low selectivity in water purification. With the addition of LiCl, membrane flux increased threefold, from 65.3 $L/m^2 \cdot h \cdot bar$ to 171 $L/m^2 \cdot h \cdot bar$, while rejection performance significantly improved from 64.5% to 99.5% (Ali et al., 2022a).

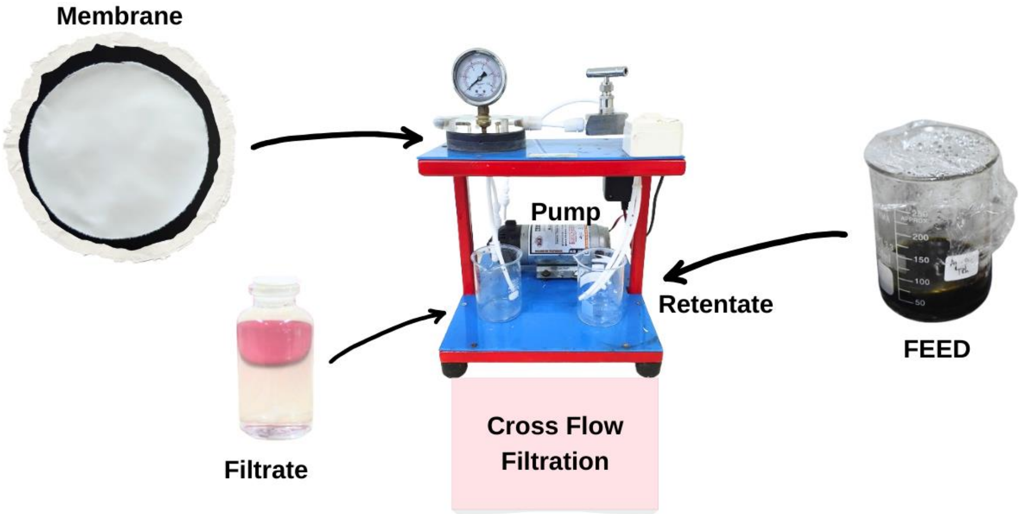

Figure 3. Schematic illustration of the filtration process

The filtrate that was produced met the requirements for clean water or water fit for human consumption. In comparison to findings obtained without LiCl and feed, the filtrate obtained from the procedure employing utilizing a PET-B/LiCl membrane displayed better result. Excellent results in water purification can be obtained by using membranes made from PET plastic waste that have been treated with LiCl (Ali et al., 2022a). Schematic illustration of the filtration process is shown in Figure 3.

In another study (Ali et al., 2022b), the immersion-precipitation phase inversion method was also utilized to optimize membrane performance, employing zeolite NaY as a modified filler during the synthesis process. The identification of fillers was researched. The manufactured membranes' ability to filter out chromium ions from wastewater was also examined. The results revealed that the PET-W membrane was capable of achieving a water flux of 292.74 $L/m^2 \cdot h \cdot bar$ and a chromium ion flux of 544.94 $L/m^2 \cdot h \cdot bar$. The percentage clearance from the PET-W membrane rose tenfold (from 4.07% to 47.8%) with the incorporation of zeolite NaY.

A nanocomposite membrane exhibiting superhydrophilicity and resistance to organic solvents was fabricated utilizing cellulosic sheets and recycled PET bottles (Bhuyan et al., 2023). The membrane with the ideal formulation might be identified as PCM2 (PET/cellulose nanofiber/PEG), which contains 2% cellulose nanofibers, given its surface porosity, hydrophilicity, and consequent permeability. In thermogravimetric analysis (TGA), This membrane exhibited exceptional thermal stability, with an initial breakdown temperature of 350 °C. The maximum permeability of the PCM2 membrane was about 98 L/m^2 h bar when applied to the diesel oil-water emulsion system and approximately 84 $Lm^{-2}h^{-1}bar^{-1}$ when applied to the crude oil-water system.

Previous study by (Hut et al., 2024) offers a long-term approach to effective heavy metal removal and water treatment. PET ultrafiltration and PET/graphene oxide (GO) nanocomposite membranes were created using the phase inversion technique using a simple GO suspension coating method. It was found that the surface-decorated GO significantly increased the removal efficiencies of BSA and Pb ions. The 0.5 GO-PET membrane demonstrated exceptional flux performance in removing Pb ions and BSA, achieving improvements of 188% and 61%, respectively, compared to pure PET. This membrane successfully removed 100% of Pb ions and rejected 97% of BSA. Research (Kusumocahyo et al., 2020) found that increasing the polarity of the non-solvent through combinations such as water-ethanol, water-n-propanol, and water-n-butanol improved water permeate flux. Additionally, raising the molecular weight and concentration of PEG in the membrane casting solution enhanced water permeability. In ultrafiltration tests using bovine serum albumin (BSA) as the model feed solution, rejection rates reached 91%. Furthermore, variations in polymer concentration significantly affected membrane performance in surface water filtration (Istirokhatun et al., 2015).

The transformation of PET plastic waste into membranes was also explored by (Chen et al., 2023). Recycled PET plastic was converted into a superwetting PET fiber membrane with exceptional structural stability and wetting selectivity through a process involving electrostatic spinning, in-situ deposition, and surface modification. The resulting membrane features a robust pore structure, superhydrophobic and super-oleophilic wettability, and resistance to corrosion from strong bases and weak acids. With its stable porosity and wettability characteristics, the membrane efficiently separates various water-in-oil emulsions, achieving separation efficiencies between 99.0% and 99.9% and a separation flux of approximately 1100 $L/m^2 \cdot h$. Additionally, the membrane exhibits excellent reusability and stable performance, maintaining its separation efficiency after at least 40 reuse cycles. This makes it highly promising for the effective and continuous separation of water-in-oil emulsions.

An improvement in treatment of wastewater including microalgae with the use of an inexpensive PET membrane made from recycled plastic bottles (Figure 4) (Rawindran et al., 2024). The membrane demonstrated a remarkable flow rate of 156.5 ± 0.25 L/m^2h for pure water and 15.37 ± 0.02 L/m^2h for wastewater. Furthermore, the membrane achieved rejection rates of up to 99% and showed impressive efficacy in selectively eliminating a broad variety of residual characteristics. Reusing treated wastewater to cultivate microalgae led to a little reduction in microalgal density, which went from 10.01 ± 0.48 to 9.26 ± 0.66 g/g.

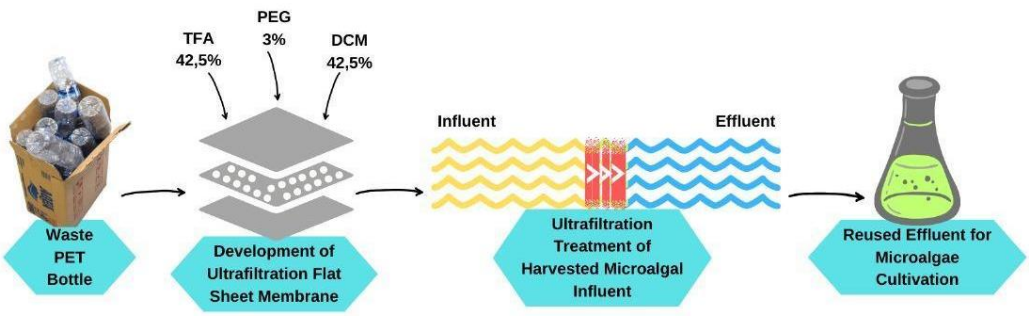

Figure 4. Schematic illustration of membrane constructed from PET plastic waste for the treatment of microalgal wastewater and subsequent reuse in microalgal production (modified from from Rawindran et al., 2024)

A nanofiltration membrane derived from recycled PET was designed for the removal of Pb (II) and Cr (VI) from both synthetic and actual industrial wastewater. Zinc Oxide Lepidocrocite nanoparticles (ZnO/y-FeOOH) were utilized as hydrophilic agents in varying concentrations ranging from 0.5% to 1% by weight. The membrane achieved a pure water flux (PWF) of 169.39 $kg/m^2 \cdot h$, with rejection rates of 93.7% for Pb (II) and 63.4% for Cr (VI). Its antifouling properties were evaluated using a milk solution, where the rPET/ZnO/y-FeOOH membrane containing 0.5% nanoparticles showed outstanding performance. It achieved a flux recovery ratio (FRR) of 96.2%, a recovery rate (Rr) of 90.21%, and an irreversible fouling ratio (Rir) of 3.001%. These results highlight the membrane's efficiency in removing heavy metals from industrial wastewater (Khashij et al., 2022).

Previous study made membranes for aqueous media nanofiltration by using waste PET bottles (Kiani et al., 2021). As two separate coagulation baths: methanol and water were employed, Xanthan gum (XA) was incorporated into membranes as a hydrophilic additive. PET/XA membranes prepared using methanol as the coagulation medium demonstrated enhanced hydrophilicity and outperformed those produced in water for nanofiltration of diltiazem aqueous solutions, despite having an identical XA content. The methanol coagulation bath achieved the highest rejection efficiency (97.6%) for PET/XA membranes containing 0.25% XA by weight.

A straightforward and adaptable approach was implemented for surface chemical modification and a sequential electrospinning process to produce a polymers Janus membrane for purification and oil/water separation (Xiong et al., 2022). The separation of water-in-oil emulsions exhibit a separation efficiency of 99.5% and a flux of 19,200 L/m² h, while oil-in-water emulsions achieves an efficiency of 99.7% with a separation flux of 1,770 L/m² h. Janus membrane preserved asymmetric wettability. It is crucial to have a flexible approach for fabricating PET Janus fibre membranes, and waste-derived membranes with moderate fabrication techniques exhibit notable separation efficiency, outstanding mechanical property, and strong antifouling activity.

PET bottles were repurposed to create membranes for bioreactors used in wastewater treatment, specifically for producing ultrafiltration flat-sheet membranes (Pongmuksuwan and Kitisatorn, 2022). The influence of various non-solvents, such as water, ethanol, EG, and PEG, was investigated as additives during membrane fabrication. Membranes synthesized using ethanol displayed a finger-like structure, while those fabricated with water as the non-solvent exhibited a hybrid structure combining macrovoids and sponge-like formations, as shown in the findings. Due to its nonporous composition, the membrane fabricated from EG was unsuitable for use in membrane applications. The membrane made with ethanol and water can have its pore size increased by adding PEG as an adjuvant.

The benefits of employing MBR technology include its scalability, lack of chemicals or additives, good effluent quality, reduced sludge production, and lower energy consumption as compared to traditional treatments (Iorhemen et al., 2016). Nevertheless, there are drawbacks to using MBR technology, such as fouling issues and high membrane replacement costs over time (Eccles, 1997).

A study assessed how common microplastics (PET) affected the membrane bioreactors' (MBR) activated sludge performance (Yi et al., 2022) When administering 60 particles/L continuously, there were little effects on the effectiveness of biological clearance. Nevertheless, additional research showed that the buildup of PET particles had a negative effect on dewaterability and settleability. The possible impacts the impact of PET microplastics (PET-MPs) on a membrane bioreactor indicated that reactor performance was not substantially influenced by exposure to 10–30 mg/L PET-MPs; however, the efficiencies of chemical oxygen demand and NH4+-N removal were altered. were significantly reduced by 50 mg/L PET-MPs (Zhang et al., 2023).

4.2. Concentration Diffusion

Fossil fuels are finite and harmful to the environment, exacerbating climate change. There will soon be a move to renewable energy (Liu et al., 2023). Wind and solar energy dominate the renewable energy sector; but, due to their intermittent nature, alternative sources like salinity gradient power, which produce no greenhouse gas emissions and offer substantial, accessible supplemental energy, must be utilized to meet global energy demands (Zoungrana and Çakmakci, 2021). Utilizing membrane-based technologies, a mixture of freshwater and saltwater can produce approximately 3 kJ per liter (Logan and Elimelech, 2012). The blue energy extracted from the "salinity potential" aggregate resource of all river effluents is around 2.4–2.6 TW worldwide, equivalent to the present global electrical consumption (Jia et al., 2014).

Numerous systems have been devised to exploit the energy from salinity gradients, including pressure-retarded osmosis (PRO). and reverse electrodialysis (RED) (Lee et al., 1981). The latter focuses on producing energy by potentially using the gradient of salt that exists between river water and seawater (Hong et al., 2015). Ion exchange membranes preferentially facilitate the movement of counter ions when solutions with varying salinities are combined. This enables the transport of anions and cations in opposite directions, producing ion flow.

A porous membrane composed of cylindrical nanochannels made from PET was covered with ion-selective hydrogel to create a heterogeneous membrane that would eliminate concentration polarization (Li et al., 2024). The heterogeneous membrane displays ion current rectification, attributed to the gel layer enhancing ion selectivity within cylindrical nanochannels. This gel layer also reduces the negative impact of concentration polarization on power generation in porous membranes. While PET porous membranes are generally inefficient for electricity generation, PET-hydrogel heterogeneous membranes can achieve a power density of 1.92 W/m² under a 50-fold salinity gradient, outperforming commercial ion exchange membranes. Other studies reveal that PA-based TFN membranes, embedded with silver-based nanocapsules as sacrificial templates, exhibit high water permeability and effective salt rejection, making them highly promising for wastewater treatment improvements (Istirokhatun et al., 2022).

4.3. Gas Separation

The separation of gases using thin barriers known as membranes is a dynamic and quickly evolving field. Membranes are employed to segregate gasses from mixtures by allowing the components to permeate them differentially. Membrane gas separation possesses a diverse array of uses in natural gas processing processes. The elimination of acidic gases and the recovery of heavy hydrocarbons are currently marketed and possess the greatest potential for development in the forthcoming decade (Scholes et al., 2012).

Additionally, PET membranes were successfully fabricated using recycled plastic bottles (Tamam Ibnu Ali et al., 2023). The PET-PBX membrane was combined with Pebax polymer and further modified with zeolite fillers (PET-PBX-ZY). Incorporating 9% Pebax increased the permeability of the PET membrane to CO_2, CH_4, and H_2 gases by 750%, 600%, and 2500%, respectively. The highest CO_2 permeability in CO_2/CH_4 separation was achieved with the 9% PET-PBX membrane, showing a 21% improvement over the unmodified PET membrane. Furthermore, integrating zeolite NaY filler into the PET-ZY-PBX membrane enhanced CO_2 permeability by up to 1044%. The PET/ZY/PBX membrane demonstrated superior performance compared to other polymer membranes, achieving a 1044% increase in CO_2 permeability, a selectivity improvement of 302.1% for CO_2/CH_4 separation, and the second-highest selectivity for CO_2/N_2 separation.

The investigation into the effects of varying Pebax concentrations on the PET membrane highlighted its pivotal role in regulating gas separation permeability and selectivity. The incorporation of Pebax significantly modified and improved the PET membrane's gas separation performance. Notably, the 9% PET-PBX membrane demonstrated a remarkable increase in permeability for H2, CH4, and CO2 gases, with enhancements of 750%, 600%, and 2500%, respectively.

Furthermore, findings from the gas permeation study revealed that adding zeolite filler resulted in the 9% PET-ZY-PBX membrane achieving the highest increase in CO2 permeability, reaching an impressive 1044%. The inclusion of inorganic fillers, such as Zeolite-NaY, within the polymer matrix can influence gas separation properties. This is due to factors like the stiffness of polymer chains and potential pore fouling, which may impact overall gas permeability.

5. Advantages and Challenges

The production of membranes from PET waste offers several significant advantages, particularly in terms of both environmental and economic considerations. A notable advantage is the reduction plastic trash has become a significant global issue. We can mitigate the environmental consequences of plastic pollution by transforming PET waste, which is prevalent found in plastic bottles and packaging, into operational membranes. This recycling approach not only diverts PET away from municipal waste, but it also minimizes the demand for new raw materials, lowering the total carbon emissions associated with membrane manufacture.

5.1. Advantages of Using PET Waste for Membrane Fabrication

Over the past 20 years, membrane technology has become very prevalent. The key factors driving membrane technology is attractive because to its user-friendliness, versatility, simplicity, and low energy consumption in comparison to alternatives. methods like precipitation, extraction, adsorption, and distillation (Asad et al., 2019). The use of membranes is extensively utilized in several applications, including water filtration (Goh et al., 2019). PET membranes have consistently exhibited their capability for membrane manufacture, offering advantages such as recyclability, solvent and chemical resistance, high flow rates, and commendable selectivity.

Another major advantage is the adaptability of membranes made from PET waste. Precise engineering of these membranes with specific microstructural features, such as various pore diameters and surface properties, can improve their performance in a variety of applications. PET membranes can be tailored to specific applications in water filtration, gas separation, and biomedical science by modifying these properties. PET waste-based membranes are adaptable and customizable, rendering them suitable for a diverse array of industrial applications.

5.2. Challenges in Membrane Fabrication from PET Waste

There are a number of challenges to producing membranes from PET waste. The complexity of processing PET waste in order to get the desired membrane properties is an inherent challenge. Impurities or irregularities in PET waste might reduce the finished product's quality. Cleaning, altering, and transforming PET trash into useful membranes is a resource-intensive process that requires specialised equipment. This can result in greater production costs and longer manufacturing schedules.

The relatively high cost of membrane materials, particularly in the industrial setting, continues to be a barrier to advancements in membrane technology. Additionally, these high-cost materials are often not eco-friendly and lack sustainability. Consequently, developing low-cost, environmentally friendly, and "green" membrane materials remains a significant challenge for future research efforts (Ali et al., 2022a).

In addition, while PET waste-based membranes can be constructed to have a high level of permeability, they may initially lack the selectivity required for some types of applications. To improve membrane performance, additional treatments or blending with other materials may be required, complicating the manufacturing process and raising costs even more. Scalability is a hurdle when trying to build large-scale manufacturing processes that maintain constant quality and performance, particularly in locations with limited technological infrastructure.

Rather than providing solutions, the goal of this discussion is to highlight the issues associated with recycling plastic for membrane manufacture. The variety in quality and diversity of plastic waste is a key barrier to waste plastic membrane technology. The differences in content and features of plastic waste from diverse sources exert a considerable influence on the consistency and efficacy of the resulting membranes. This variety creates difficulty in standardizing production techniques and achieving uniform outputs across multiple batches.

The lack of consistency in research methods and protocols across different countries is an additional significant challenge. The prevalence of several procedures and approaches complicates the process of comparing results and duplicating studies, which is critical for validating findings and advancing knowledge. This lack of uniformity can stymie collaborative efforts and the development of optimal methodologies, which are critical for improving the field of membrane technology created from waste plastic. Establishing widely recognized standards and goals is vital for advancing technology and facilitating international cooperation.

6. Future Perspectives

The manufacturing of membranes from PET waste has immense promise, but it is not without challenges that must be addressed in order to fully realize its capabilities. Several critical ideas must be implemented in order to develop PET waste-based membranes in an efficient and scalable manner. First and foremost, it is critical to create recycling and processing technologies to address concerns about the quality and consistency of PET waste. Implementing more effective cleaning and sorting technologies will effectively eliminate pollutants, ensuring a consistent raw material for membrane manufacture. Furthermore, the development of new chemical modification techniques for PET can improve its performance attributes, rendering it appropriate for a broader range of applications.

Future study should focus on optimizing membrane design and efficacy. To enhance the selectivity and permeability of PET-based membranes for particular applications, it is essential to consider their microstructural features, including surface chemistry, and pore size distribution, must be optimized. The incorporation of nanoparticles or other additives into PET membranes has the potential to improve their performance, enhancing their efficacy in numerous applications, including water filtration, gas separation, and biomedical use. Optimizing the scalability of membrane manufacture from PET waste is also critical. It is critical to create large-scale manufacturing procedures that maintain consistent quality and performance throughout production batches. The successful implementation of high-volume production while adhering to industry standards involves major technological and infrastructure investments.

Furthermore, it is critical to foster collaboration and consistency among university and industrial research institutes. The use of standardized protocols and benchmarks can improve the capacity to compare findings and duplicate studies, resulting in faster advancement in membrane technology. Incorporating these recommendations will advance the field of PET waste-based membrane manufacture towards more sustainable, efficient, and widely recognized solutions, leveraging on the ecological and financial advantages of recycling PET trash.

6.1. Sustainable Approaches

Global industrialization and urbanization phenomenon, the concept of "sustainability" has gained relevance. Rapid development has led to pollution of natural resources, posing a hazard to the ecosystem. Pollutants are being released into the environment without sufficient treatment, posing shorterm and longterm health risks to living species. Pollutants differ in physical state, chemical content, and size. To address this risk, a multifaceted approach is necessary, including the use of membranes. Membranes can be changed to remove pollutants, which is their main advantage (Lim et al., 2021).

Polymeric membranes are now used to treat wastewater using improved oxidation, bio-activated sludge, and adsorption technologies (Martini, 2022). Pollution has been reduced through strict environmental rules. (Yadav et al., 2022), suggest that Zero Liquid Discharge (ZLD) use membranes as the foundation and combines different separation procedures to enhance treatment efficiency. Innovative wastewater treatment technologies, such as integrating membrane technology with in-situ chemical oxidation, can reduce scale and sludge formation and increase catalyst reusability (Yan et al., 2021).

6.2 Research and Development Needs

The range of chemical materials that can be obtained from PET waste is predicted to increase significantly with the advancement of technologies for chemical recycling and upcycling; however, successful implementation of these processes will depend on process improvement, energy and chemical consumption optimization, and process optimization. Via adjusting the surface characteristics (via doping or functional group formation) and nanostructure (particularly porosity), the performance of these high-value materials can be enhanced. In addition, studies on the fabrication of membrane technology from plastic waste need to be improved.

7. Conclusions

The future prospects of membrane technology utilizing waste plastics, especially PET, appear bright as technological advancements and heightened global engagement are anticipated to propel the creation of efficient, cost-effective, and sustainable solutions. PET, commonly utilized in the production of bottles, has played a notable role in environmental issues owing to its restricted recyclability. Transforming waste PET into valuable membrane materials offers a creative solution to tackle environmental and economic issues.

Although existing technologies encounter difficulties in obtaining virgin monomers from waste PET, the idea of using PET bottle waste as a material for membrane fabrication is becoming increasingly popular. The performance of PET membranes is dependent on the properties of the material and the techniques used in production, highlighting the importance of resistance to fouling, as well as mechanical and thermal stability, alongside innovative manufacturing approaches. Incorporating suitable additives can improve the durability and tensile characteristics of PET membranes, opening up opportunities for wider applications.

This research emphasizes the environmental and financial benefits of converting waste PET into commercially viable membrane materials. Nonetheless, additional research is crucial to create dependable, efficient, and scalable conversion processes that yield cost-effective, high-performance membranes appropriate for various applications. Ongoing collaboration and advancements in technology will be essential in addressing current challenges, promoting sustainable practices, and developing solutions for a cleaner, more sustainable future.

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Conflict of Interest

All the authors assert that they possess no identifiable financial conflicts of interest or personal affiliations that may have seemingly impacted the work presented in this study.

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