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Chemical engineering of separation membrane, interfacial strategies, and mathematical modeling: a thorough analysis

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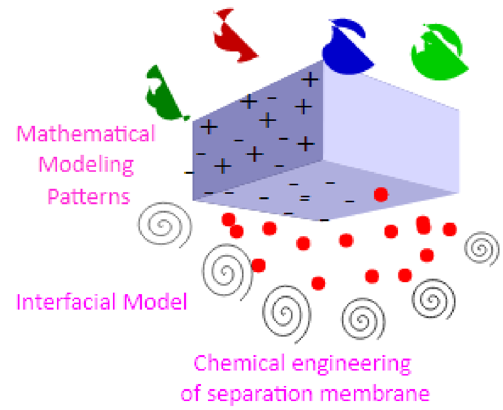
ABSTRACT

The rapid advancement of membrane science and technology is dependent on significant advancements in the materials used in membrane design, production, and modification. Membrane separation methods are mostly used in wastewater treatment, water isotope separation, acid concentration, and other applications. The primary goal of this review is to present the current principles and applications of various separation membrane technology, interfacial designs, transport, and separation processes through investigations and significant contributions framed in fields of its application. New nanotechnology-based materials have been used to overcome the constraints of the traditional membrane-separation technique; the most intriguing of efficient materials for the manufacture of nanocomposite membranes are the metal-organic frameworks (MOF)-based membranes. Analysis via mathematical modeling indicates a possibility of further improvement in recently developed smart membranes towards more advanced operations. The review discusses the membrane technology, latest methods, and materials developed along with computational aspects applied towards the concerning fundamental principles and practical applications of separation technology.



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INTRODUCTION

In chemical designing and physical processes, the separation membranes play a major role in the separation of the mixtures of different chemicals and constituents.[1] These outfits and techniques are widely used in different procedures, including processing industries and purification processes.[2] Separation membranes are well-considered for study in chemical technology and engineering for the separation of different mixtures in various applications.[3] The key properties of separation membranes include their ability to control the permeation rate of crude chemicals. These separation membrane technologies are enriched with specific features and could perform separating tasks inclusively.[4] The separation membrane is developed through innovative engineering that is an effective and efficient route compared to other procedures including, reverse osmosis, microfiltration, and ultrafiltration.[5] The performance of separation membrane technology based on fine pores. Hence, these membranes are utilized in scientific practices and industrial drives extensively. The separation membranes can operate at various pressures and execute well in diverse circumstances. These filtration procedures and techniques can also be implemented in different chemical and physical settings.[6] Moreover, the membrane-based separation technologies are considered environmentally friendly outfits that are intended to pact with environmental issues such as climate change and global warming.[7]

The rapid growth of membrane science and technology hinges on the notable improvement of materials used for designing, fabrication, and modification of membranes. The advances in membrane development and the up-gradation of concerning

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equipment finally displayed its impact on the evolution-allied with the systems and engineering needs.[8] Applications of the separation membrane in various processes, including in the laboratory and industrial operations depends upon separation membrane technology along with the technical significance and commercial impact.[9]

In separation membrane technology, one component of a mixture must be removed from the main mixture by permeating it through the membrane via fine pores freely and by hindering other components.[10] The existing industrial membrane separation processes and main segments of current membrane technology are discussed here with the membrane transport modeling and carrier-facilitated transport, followed by illustrating the applications of membranes using nanocrystals, and interfacial designs.[11] The main objective of this evaluation artifact is to present principles and applications of various separation membrane technology, interfacial designs, engineering and architecture of metal-organic framework separation membranes, transport, and separation processes by the unique perspectives of investigations and way of important contributions framed in the fields.

Recently, physicists, chemists, and engineers have designed new strategies to develop advanced designs of separation membranes.[12,13] This elucidation was tested during the selective removal of certain chemical species. As a result, different processes, which are included in steps of membrane separation, have been drawn in industrial, and governmental laboratories since its discovery. Therefore, significant advances have been made in many dimensions of separation membrane technology at present as well as in the development of new membrane materials that can be used for designing a higher quality of selective membranes and will be used in the process of designing.[14] Shortly, these technical findings will be applied in an impressive variety of claims allied to separation membrane machinery.

Furthermore, a lot of research is going in the area of separation membrane technology and rapid growth was observed in the detection of various applications. The separation membrane technology, such as the classification of transport and separation processes (unit operations), molecular separation, membrane transport modeling, use of nanocrystals in interfacial designs, microstructural and interfacial designs, microstructural engineering, and architectural design of metal-organic framework based membranes have also conferred due importance.[15,16] The review discusses the different dimensions of separation and filtration techniques along with the associated principles as well as parallel techniques including electrodialysis, reverse osmosis, ultrafiltration, microfiltration, and gas separations in this radically analyzed valuation.[17]

Transport and Separation Processes (Unit Operations)

Separation and transport processes are at times collectively involved during separation in different chemical, physical, or biological processes separately. These procedures further break them down into a series of separation processes and distinct unit operations.[18] The unit operations and processes are counted for clearing existing concepts and for drawing the differences. Even though it is a modern and descriptive term that has come into existence and is designated specifically in a separation process. Conversely, the term "unit operations" was reassured.[19] Furthermore, a proper understanding of momentum, separation processes, heat, and mass transfer during the research in chemical engineering can further expose the hidden aspects of the separation process.[20] Chemical engineering and separation membrane technology are vast subject matter. Therefore, it is a series of difficult concepts, and hence researchers must be ready to encounter them every time. Various themes of chemical engineering are explaining the mechanics of chemical reactions, elements, factors, heat recovery system, mass transfer steady-state, and unsteady-state heat transfer, and generating products (fig. 1).[21]

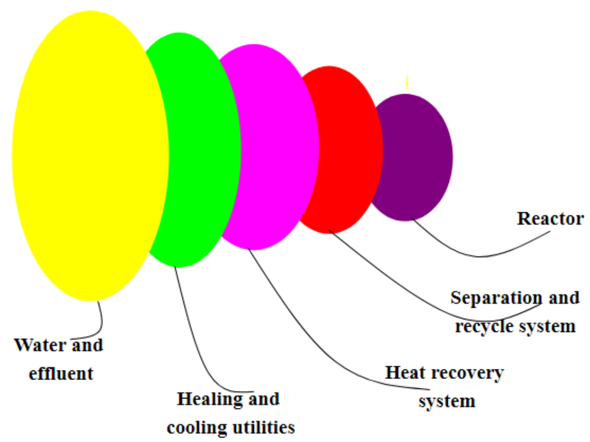

Figure 1. Key research, development, and demonstration of a road map in industrial application.

Not long, the testified investigations on the principles of transport and separation process offer a unified and up-to-date output of all these topics that are underlined now. In-depth, modernizing imitates separation membrane technology. These aspects of separation procedures dissolve persisted confessions in the field of chemical engineering and separation membrane technology.[22] The task of separation of components in a mixture depends always on the difference in the physical properties of mixture constituents.[23] Based on the nature or physical mechanism of separation, various separation processes such as mechanical separations, diffusion, and membrane separations are classified. Henceforward, there is importance of the essential principles underlying transport processes and various aspects of momentum transfer, including unsteady-state and convective mass transfer.[18] Transport and separation procedures cover key separation processes, including evaporation, ion exchange, absorption, distillation, adsorption, extraction, drying, humidification, leaching, crystallization, settling, centrifugal separation, dialysis, gas membrane separation, reverse osmosis, filtration, ultrafiltration, microfiltration, and more.[24]

The technical innovation for advancing rational designing portate a separation process and can be applied as an alternative or as the main tool.[25] Instead of ongoing technology of separation processes that are based solely on relative volatility (distillation), the aforesaid strategies can be emphasized as a cross-cutting, cohesive, translational methodology for identifying and prioritizing the solutions for the existing technical challenges that followed at the molecular level.[26] These alternatives of separation membrane can be more effective in energy-efficient separation technologies, interfacial designs, and chemical engineering of transport.

MOLECULAR SEPARATION: CHEMICAL ENGINEERING OF TRANSPORT, AND SEPARATION PROCESSES

The elucidation of basic transport phenomena of unit operations of separation membrane, it can be a chemical or physical process or both, has a tremendous impact on the separation techniques.[27] These mechanisms rely on separation membrane unit operations. The claim of membrane technology is in a straight line reliant on the filtration time. Simultaneously, the filtration performance is directly allied with it.[28] By underlining the sources of flux decline and classifying the capacity, the flux routine is one of the crucial parameters that is examined to determine the membrane entitlements. The inquiry of the consistent dynamics further ropes earlier studies. Membrane fouling and mass transport are also exposed while expressing the filtration/separation process for having a more scientific interpretation via drawing a comparison of the recent findings.[29] During the investigation, by identifying transport resistances, a novel viewpoint can be drawn that produce innovative theories on membrane fouling.[30] Therefore, such analysis need to be done on the mechanisms of diffusion mechanisms in the membrane pore. It can also be done when the mass transfer is low in high-pressure membranes altogether. These fundamentals will offer properly applicable mass transfer mechanisms. Such types of deeper lookouts are providing a comprehensive, unified, up-to-date monitor system to transport in separation processes.[31] Additionally, a thorough understanding of momentum, heat, mass transfer routes, and separation procedures will modernize the values of transport and separation processes. These interpretations are providing a thorough update and discover the latest applications by exploring the essential principles and practical claims.[32] Finally, it will offer unified and up-to-date aspects of the topic.

The replying strategies for solving the existing separation problems that are encountered in emerging technologies of different fields including biotechnology, green technology, energy storage and conversion, biobased feedstock products, and resource recovery and recycling.[33] Thus, this section also offers knowledge to the experts of the field and explores a critical assessment of the state-of-the-art of novel approaches in separation and purification applied. The discussion also represents molecular separation: chemical engineering of transport, and separation processes, the phenomenon of mass transport, and separation with a focus on the dynamic aspects that power speed and the effectiveness of the equilibrium separation route.[34] The up-gradation of the techniques of separation and purification is based on the findings of experimental studies and theoretical analyses. These occurrences connected with the processes that improved the development of simulation, equipment design, and fabrication.[35] The emphasis laid down on the learning of separation membrane technology, interfacial designs, chemical engineering of transport, and separation routes that also covered the essential principles underlying momentum transfer, steady-state and unsteady-state heat transfer, transport processes, and mass transfer.[36] The important phenomenon include evaporation, drying, humidification, ion exchange, extraction, leaching, absorption, distillation, adsorption, crystallization, dialysis, gas membrane separation, microfiltration, settling, centrifugal separation, reverse osmosis, filtration, and ultrafiltration.[37]

This clarification can always originate upgraded separation procedures or principles that can be applied to draw new applications and the same can be implemented directly for identifying separation techniques. Lots of separation procedures are dynamic and can succeed by diverse transport rates of the components. Mass transport occurred via specific molecular motion that is normally termed “diffusion.” Now, several types of diffusion were categorized such as molecular diffusion, forced diffusion, pressure diffusion, and thermal diffusion. Advantages of energy efficiency, simplicity, scalability, and small environmental footprint are the components of membranes that are favored molecular separations by own. Various emergent microporous organic materials have revealed excessive potential as building blocks of molecular separation membranes, that not only assimilate the rigid, planned pore assemblies and desired immovability of inorganic molecular sieve membranes but also display a high degree of liberty to form chemically rich combinations.[38] Hence, to have a deep insight into the essential connections and features of these microporous organic material-based membranes, the concept of organic molecular sieve membranes was considered with the attention on the precise assembly of membrane provisions and proficient intensification of membrane routes. To attain beneficial separations, the diffusion of specific types in a mixture, is, defined as interdiffusion. This class of procedures is of greater interest in contrast to self-diffusion in a scheme having only matching molecules.[39] The diffusion procedure can be purely defined as a one-dimensional model.

MODELING OF SEPARATION MEMBRANE AND TRANSPORT PROCESS

Nanofiltration (NF) membranes are used for softening of water or hardness removal (Ca^{2+} and Mg^{2+}) from water or any solution. NF membranes possess wettability and surface charge as main surface properties.[40] It is a type of pressure-driven membrane that has properties in between those of ultrafiltration and reverse osmosis membranes. Nanofiltration membranes can make available a high water flux at low operational pressure for upholding an upper salt and organic matter rejection ratio.[41] The nanofiltration process has the benefits of ease of operation, reliability, and comparatively low energy consumption as well as highly efficient pollutant removal. These parameters directly reduce scale founding on the equipment convoluted in both reverse osmosis and thermal desalination routes.[42] Therefore, nanofiltration membranes have received interest worldwide. Recently, nanofiltration membranes were used in pre-treatment unit set-ups in both thermal and membrane seawater desalination practices. This has resulted in a reduction in chemicals used in pre-treatment processes as well as a decrease in energy consumption and water production costs. Therefore, it has led to more environmentally friendly processes.[43]

A high-performance membrane can be acquired on controlling these properties by incorporating nanomaterials into matrices of the host. An increase in surface hydrophilicity by the addition of hydrophilic nanoparticles can lower the fouling of NF membranes.[44] Integration of carboxylated MWCNTs for modifying polyamide NF membranes has been studied. In a recent study, iron-based nanoparticles significantly retained dye due to strong forces of repulsion between functional groups of nanomaterials and dye.[45] Application of iron oxide nanoparticles based on novel magnetic materials for removal of heavy metals from the aqueous systems developed as highly efficient and cost-effective nano adsorbents.[46]

The surface modification approach enhanced their stability and efficiency in the water. Magnetic nanoparticles possess an important magnetic property that helps to remove easily in the presence of a magnetic field.[47] The reuse of magnetic nano adsorbents will decrease the economic burden. Magnetic nano adsorbents technology for water remediation is more convenient and appropriate for removing and separating heavy metals. Before their bulk application health effect and fate into an environment of magnetic base nanomaterial, these points should be addressed. Membrane distillation (MD) is a process for separating mixtures using a microporous hydrophobic membrane.[48] The membrane distillation technique is given preference over conventional methods for separating the mixtures due to their high rejection and their potential in improving energy saving.[49] MD is a well-suited technology that was used for separation processes wherein water is applied as a major component in the feed solution. In MD, at least one side of a microporous hydrophobic membrane is in direct contact with an aqueous solution. Partial pressure difference induced by the temperature gradient between two sides of the membrane causes mass transfer through membrane pores.[50] During the MD process, liquid molecules are not allowed to infiltrate due to the hydrophobicity of the membrane, and only vapor molecules can pass through the membrane walls. The separation membrane is featured as the best technology because it offered several advantages comparatively other technologies in practice (figure 2).[51] Furthermore, it had already been accepted and earlier proven to be a trustworthy technology.

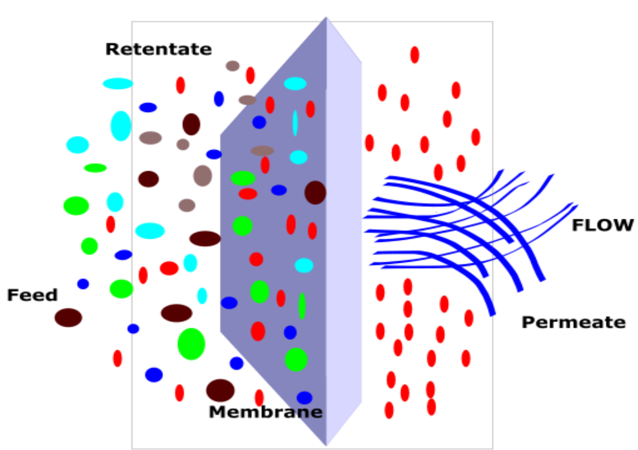

Figure 2. Process of separation membrane operations.

Now, mathematical modeling is highlighted as an important aspect of all membrane operations. Obtained data provide useful information about the features of the separation membrane and attained mathematical statistics are useful in designing a more advanced separation membrane that will be better based on the performance of the membrane.[52] The ultrafiltration, microfiltration, nanofiltration, and reverse osmosis are different types of membranes that have diverse transport mechanisms. Consequently, their models must be checked by mathematical modeling to predict their performance under different conditions.[53] Accurate analysis and data interpretation are the main features of reliable modeling, and therefore, this scientific analysis dealt with the difficulties be existent in membrane operation. By applying this scientific scheme, complications can be recognized in the initial stage.

Mathematical modeling is a preventive method that can be applied to reduce errors in the design and procedures.[54] Hence, the way mathematical modeling is applied for bettering separation membrane procedures is also crucial. Thereafter, it will approach the existing problem with a better understanding of the way that will enhance its long-term performance. The authors anticipated that the use of mathematical modeling should be simple so that it can be used or easily applied for its betterment.[55] Simplification of these mathematical modeling methods will increase its ease of usage and promote routine data analysis ways. The desired goal to use these modeling ways can be achieved by comparing the data of the simplified models and realistic models under similar conditions.[56] These procedures are specifically applied to have experimental data in one way to test the simplifying assumptions and existing results. Additionally, the mathematical modeling practicality can bring new insight into unsolved aspects of the separation procedures. All models in use, no matter how scientific, are they and always in practice, so in that case, sometimes few of them are less complex than the real system.

Moreover, mathematical modeling will also be the key and will predict some new aspects that can be applied to have better designs.[57] In practical terms, there are always chances of failures, at this juncture, the mathematical modeling can explain, observe results and identify the causes of the failures. Identified defects can be removed from earlier stages by underlining practical hurdles. Furthermore, these methods can refine the separation membrane models and explain new terms of the system. The expanding interest in separation membrane research redefines the main role of membranes in physiological processes.[58] Mathematical modeling answered all facts and undisclosed causes that were unknown to date and can solve these important membrane transport problems, which are still unsolved.[59] Some of these unsolved problems can also be related to the complex molecular interactions and not addressed well in the past or poorly explained. One of the first problems for a researcher is to identify problems in the transport processes and must be adequately described in straightforward standings.[60] In the end, it exposed the role of mathematical modeling and recommended removing the existed difficulties.

MICROSTRUCTURAL AND INTERFACIAL DESIGNS

Membrane separation processes are mainly applied for wastewater treatment, separation of water isotopes, desalination, the concentration of acids, treatment of agro-food, and other applications for which water is the major component present in the feed solution to be separated.[61] Currently there are various technologies available for the separation of mixtures among which most processes require high energy and chemicals which can be toxic. The membrane separation process is less complicated and does not either require any toxic chemical or produce any toxic product.[62] This technique uses a hydrophobic microporous membrane for the separation processes. The driving force of membrane separation is the partial pressure difference between the feed-membrane interface and permeate-membrane interface. The aqueous solution on the feed side must be hydrophobic to prevent the penetration of the solution unless the hydrostatic pressure exceeds the liquid entry pressure. Initially, the conventional membrane-separation process was being used for water purification, but these methods were found to consume a considerable amount of energy, which limited the application of this method.[63] The other disadvantages are fouling tendency caused due to pouring blockage by foreign particles present in the mixture, high cost, less selectivity, less performance, etc. To overcome these limitations and enhance the performance an alternative approach is required.

Nanotechnology put an end to these limitations of the conventional membrane-separation process and in the last decade, this new technology has vastly been implemented in the purification of water. The employment of nanoparticles has enhanced permeability, flux recovery, catalytic activity, antifouling, stability so on.[64] The nanomaterials, which have been reported as efficient materials for the fabrication of nanocomposite membranes, are specifically titanium dioxide, silica, silver, zeolite, carbon nanotube (CNT), and vertically aligned CNTs.[65] They are being prepared in different morphologies and different experiments, as well as designed to develop membrane materials. The classification of membrane mainly depends upon the composition of fabrication material. A classification has been drawn that is depending upon the composition of these separation membranes as organic and inorganic membranes.[66] Inorganic membranes are fabricated from inorganic materials. These types of membrane are further classified into ceramic materials. Organic membranes consist of two asymmetric layers, a thin porous support layer and a less porous layer above it.[67] The top layer carries the separation process and the support layer provides the strength to the top layer.

NANOCRYSTALS, INTERFACIAL DESIGNS, AND TECHNIQUES

The interfacial design and interaction were explored between various nanoparticles ranging in different biochemical or biological worlds as well as their electrochemical properties in detail.[68] As, the hydrophobicity and hydrophilicity of components demonstrated the feasibility of the design strategy that may also be extended to other properties, for example, conductor/insulator, p-type/n- type semiconductor, or ferromagnetism/anti-ferromagnetism, for the design of microcrystal.[69] The interfacial interaction between various nanocrystals is investigated by thermogravimetric and differential scanning analyses, including SEM TEM, Raman spectrum, X-ray photoelectron energy spectrum XRD and Fourier transform infrared spectroscopy, etc.[70] In addition to the design of novel nanostructures, a fundamental understanding of interfacial interaction between various layers or metal-to-metal interaction is necessary. The interfacial interaction between the metal oxide and nanocarbon (graphene, carbon nanotubes, and even other carbon materials) in nanocarbon/metal oxide composites are associated with their preparation methods.[71]

To design the nanocrystal, the stoichiometric and nonstoichiometric makeup of compounds was used to clear the actual picture of interaction with other interfacial structures. Compared with other nanocarbons, the thin 2-D nanostructure and uniform hybridization of carbon atoms of graphene provide an ideal model to investigate in detail the interfacial interaction between a metal oxide and carbon.[72,73] Sometimes it varies with the predesigned synthesis process because of their various interactions like covalent or electrostatic interactions between them. However, the interfacial interaction between metal oxide/metal and nanocarbon and various nanocrystals is of great interest importance because they not only control the catalytic growth of carbon nanotubes or graphene but also play a crucial role in promoting various applications of carbon-based metal oxide composites.[74] The coupling influences lifespan in a straight line and definite dimensions of graphene-based anode constituents.[75] Enhancing or modulating the interfacial interaction between nanoparticles and nanocarbons can lead to enhancing the biochemical and biological world. The foremost aim is to characterize and analyze the data obtained by various scanning techniques and leads to minimum non-stoichiometric defects.[74] This will lead to a high range of nonstoichiometric microstructure for a wide range of users and applications.

Nanomaterials fabricated like mineral NPs, metallic NPs, CNTs, and graphene are effectively combined with biological constituents to attain new properties.[76] The properties like complex actuation, superior thermal and electrical conductivity, controlled gas barrier properties, and distinctive optical properties.[77] These build-in properties, the combined biological and synthetic constituents aided by powerful interfacial connection, eventually increase the structural performance. NPs with their confirmed interfacial structure and their specific morphology, size, and magnetic properties are useful for many applications, but still, there are some health hazard concerns due to their uncontainable procedure and ejection to the normal setting.[78] These features should be well-thought-out to search for the claim of NPs more suitable and environmentally responsive.

Naturally, derived materials with a long range of applications are attractive for high-performance and functional because of their renewability, biocompatibility, biodegradability, flexibility, and the availability of multiple reactive sites for introducing novel functionalities.[79] The contribution of numerous electron microscope techniques like SEM STEm XRD-based data will be introduced and discussed.[80] The principal techniques for TEM specimen preparation, thin sectioning, metal shadowing, negative staining, and plunge-freezing (vitrification) of thin aqueous samples are observed, with a selection of published images to emphasize the virtues of each method.[81] The imaging technique and three-dimensional reconstruction are illustrated minutely. The same is employed in electron crystallography and reconstructions from helical structures, 2D membrane crystals, and single-particle 3D reconstruction of icosahedral viruses and macromolecules.[82] The ongoing development of new software, data analysis gives a major contribution to interfacial designs. In this review, we discuss the separation membrane technology, interfacial designs, chemical engineering of transport, and separation processes: a radical analysis.

Engineering and Architecture of Metal-Organic Framework Separation Membranes

The metal-organic frameworks (MOFs), zeolites, and graphene oxides were also useful in the designing and development of molecular sieve membranes. As, a constituent, MOFs are fascinating materials that are considered in the class of solid crystalline substances that can perform self-assembling via the coordination of metal ions or clusters with organic ligands.[83] Metal-organic frameworks (MOF) are synthesized materials assembled with metal ions or metal ion clusters bridged via organic ligands.[84] Inorganic metals, metal ions, and materials are the main constituents that were used in the preparation of the MOF-derived separation membranes. Most MOFs have porous structures that can easily be synthesized in a lab having various versatility in their features. MOFs owned intrinsic porous characteristics, a high grade of functionalities, and ample chemical versatility.[85] These metal-organic compounds displayed well-defined pore structures and have large surface areas.

Considered MOFs also revealed extraordinary adsorption features. Recently, these MOFs were applied in several separation applications and executed well as per the necessity of the scheme.[86] The methodology espoused for the creation of MOF-based separation membrane that will greatly influence its industrial performance and separation potential. In some cases, polymers and their materials were employed in the designing and preparation of separation membranes.[87] Moreover, the hollow fiber substrates have also been incorporated that helped to improve the membrane areas per volume. These characteristics displayed significant research interests while these are used in different procedures of membrane-based separations. For example, the zeolite-imidazolate frameworks (ZIFs) are a subclass of MOFs that have great features that can attract research attention.[88] These ZIFs are utilized in the formation of high-quality membranes and revealed great potential in hydrocarbon mixture separations.

Recently, various research activities have been reported for covering different fabrication strategies that were applied in developing MOF-based separation membranes. Various emerging stages of vital development were succeeded that focused on improving the liquid separation efficiency by applying well-designed MOF-based membranes.[89] Consequently, the authors underlined the importance of MOFs in the recent trends in the development of separation membranes. Different criteria were considered before the correct selection of MOFs in fabricating MOF-based membranes, and discourse.[90] Moreover, special attention was made to explore rational design strategies for manufacturing MOF-based membranes. The latest application progress has been underlined for a proper explanation including, pervaporation, organic solvent nanofiltration, and water treatment.[91] Besides, the dual-function characteristics of MOF-based membranes were applied for removing micropollutants, degradation, and antibacterial activity.[92] A need is there for further innovation in the area of MOF-based membranes to achieve a better liquid separation technique that can fulfill the persistent demands. Furthermore, newly designed and developed separation membrane should follow strict separation standards and cover the needs of environmental safety in all industrial claims.[93] In future, these materials might be used in diverse industrial applications and engineering of the separation membrane. These types of construction and schemes built these membranes highly proficient that are applied in energy-efficient separation and purification machinery, including cryogenic distillation, chemical absorption, gas separations, and pressure swing adsorption.[94] The MOFs displayed better separation performance and specific features such as permeability, long-term stability, and selectivity.[89] The underlined membranes were composed of MOF materials and offered unprecedented opportunities. These molecular sieve membranes owed high flexibility in both pore apertures and functionality.[95] These types of special materials become essential for developing MOF outfits. Henceforth, the new design methods and innovative concerned microstructural engineering were utilized in the manufacturing of MOFs membranes at mesoscopic and microscopic levels.[96,97]

The MOF-based membranes display excellent performance in innumerable routes, including gas separation, nanofiltration, and pervaporation.[98] The MOFs have inorganic substrates and in some cases, also contained polymer substrates. These combinations support the MOF-based mixed matrix membranes mechanically and boost their performance.[99] So, the MOFs was recognized as a special organic-inorganic composite material that was applied for generating some advantageous features, including large specific regular and adjustable pore structure, surface area, good thermal and chemical stability.[100] There is one drawback of these MOFs, which is that when these materials have existed in powder form, cannot be re-cycled easily.[101] Nowadays, researchers are formulating MOF-derived separation membranes, which have excellent properties, can be extensively utilized in different areas such as separation methods, industrial procedures, catalysis, metal protection, desalination and water treatment and separation optics, oil-water separation sensing, gas separation, and pervaporation.[102]

To explore these different dimensions of designing and development of conferred separation membranes, a thorough assessment is necessary that can provide an evaluation of existing engineering challenges in the separation techniques, including module design, and membrane stability.[103] These efforts might improve reproducibility for industrial scale-up. These exercises examine the upkeep of earlier findings and offer a new outlook on future study and expansion. MOFs are porous materials that showed high porosity, distinctive chemical functionalities, and have tunable pores.[104] Emphasized MOFs are utilized during wastewater treatment as the main constituent in adsorption and membrane separation. The MOFs were applied as nanofiller in thin-film nanocomposite or mixed-matrix membranes, which influenced the membrane chemistry and morphology, and improved its performance during water permeability.[105] The stability of MOF has supported the distance of positive charge per atom, and high coordination number, which confirmed the presence of hydrophobic functional groups. Such constituents improved their ability during the resistance phase coordination with water molecules.[106]

Other aspects of MOFs were discoursed in the article, with a special emphasis on MOF agglomeration that has already been identified as the main cause of deteriorated membrane performance. At this point, the future outlook was established for having a good proposition that can be significant in future expansions.

CONCLUSION AND FUTURE PROSPECTIVE

In the last two decades, enormous progress has been reported on different dimensions of the membrane and membrane-based separation techniques. These separation membranes and processes are developed for industrial use at a large scale and are useful in various applications, including hemodialysis, desalination, and separation of azeotropic mixtures. The process of membrane separation is significant in the chemical industry because that influences the energy efficiency and modularity of the procedures. Recently developed separation membranes have been used in various fields, including water treatment, biotechnology, chemical manufacturing, gas separation, biomedicine, and separation process integration. This remarkable progress in the development of separation membrane upheld various developments in industrial processes and is helpful in the concerned applications. At this time, the authors highlighted the recent development of separation membrane technology, interfacial designs, chemical engineering of transport, and separation processes.

Mathematical modeling predicted that recently developed smart membranes are capable of more advanced operations and can be used in various applications such as molecular-recognizable separation, antifouling membrane for liquid separation, ion exchange membrane for chemical production, high-performance gas separation membranes, and high-efficiency hybrid membrane separation process design. Additionally, the applications of the separation membrane are exploited in various important devices. Various important processes and concerned designing strategies of chemical engineering were also applied together to have a much more efficient outfit. Finally, the different aspects of future research directions and key challenges are considered for addressing the important issues of separation membrane that are emphasized and concluded.

Current trends in the research stressed the designing and allied routes for significant impact and sustainable procedures. The framework of the separation membrane is based on several features of used design that can be utilized for automated process, synthesis, and screening of numerous designs applied in processes, and network configurations. Testified findings were elaborated further to demonstrate the applicability of the proposed approach. Observed substantially have better impacts on earlier reported findings that were based on the designs of these membranes in the literature.

Besides, the reactions and relations parameters, the features of separation membrane, and interrelated design aspects are other key segments of these operations that materialized in the chemical industry. The process of distillation and evaporation was intensively elaborated. The processes of drying and crystallization have also been expounded. Various procedures such as liquid-liquid extraction, adsorption, and absorption, also exemplified along with the phenomena of the separation membrane. Other techniques that have similarities in chemical engineers, such as distillation procedures and packing methods also clarified along with the other details of the technology of the separation membrane.

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AUTHOR CONTRIBUTIONS

R.K. conceived the idea and trained the models. R.K. also. preprocessed the data. R.K. analyzed the results and wrote the manuscript together and supervised the project K.P. wrote the modeling membrane transport section. M.A.S. wrote the nanocrystals and interfacial designs section. Sangeetika contributed in the section named microstructural and interfacial designs. C.A.I wrote a few paragraphs of the articles and revised the manuscript. All authors read the review article and approved it mutually.

COMPETING INTERESTS

The authors have declared that no competing interest exists.

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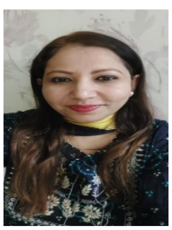

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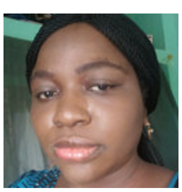

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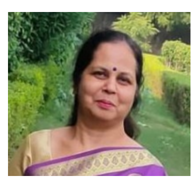

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