JOURNAL OF CRITICAL REVIEWS

ISSN-2394-5125 VOL 02, ISSUE 04, 2015

UNVEILING THE RESURGENCE OF ULTRAFILTRATION MEMBRANES: A STATISTICAL REVIEW OF UF TECHNOLOGY AND CURRENT RESEARCH TRENDS

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Abstract
Ultrafiltration (UF) is a pressure-driven membrane separation process that has transformed a banking-key technology throughout the industrial sectors achieving liquid solution fractions purification. Recombinant Protein Through Membrane Technology, Higher Efficiency, More FLux, Greater Application: Developments in membrane materials, bioreactor designs, and process engineering have extended the scope of UF (ultrafiltration) by improving its efficiency, flux rates, and application fields. During the last years, different classes of polymers (polymeric membranes) and ceramics (ceramic membranes), which have distinctive attributes in comparison to each other, have been adopted as separation materials. Composite polymer-ceramic membranes intended to exploit the 2-way interaction of their benefits. The barrier characteristics of transport such as pore size distribution, surface roughness, and chemical resistance play a role and affect both flux and separation efficiency. No waste or kind of it is irrelevant to the spheres of food, pharmaceutical, or industrial wastewater treatment industries, those are clarification, concentration and purification applications. Nonetheless, issues arise concerning the efficient mechanism of cleaning which requires more innovative developments. Coming technology is devoted to addressing the design of modules and the surface modification of membranes which will subsequently result in an enhanced fouling resistance.

Keywords: Ultralfiltration-membrane, Separation, Fouling, Cleaning, Industrial water.

I. Introduction

Ultrafiltration (UF) stands as one of the mechanical and membrane separation processes that has grown to be a critical technology for separated and purified liquid phases in most industrial sectors within a short time [1]. UF membrane is characterized by pore sizes of 1-100 nm (small pores) which allow passage of water molecules and other low molecular weight solutes, while effectively retaining macromolecules, colloids, proteins, particles, bacteria and viruses [2,3]. Micrometry which is the step that is superior to microfiltration produces membranes with smaller pores (above 100 nm). Therefore, UF ensures better separation efficiency for solutions that contain solutes in the molecular weight range that is equal to and smaller than 103 to 106 g/mol [4]. In contrast to the case of nanofiltration and reverse osmosis which use tighter membranes that are operated at higher pressures, UF has the major advantages of lower energy consumed and operating costs [5].

The most popular polymer and ceramic membranes are used most often UF [2]. Polymers in UF membranes are cellulose acetate, polysulfone polysulfone polyethersulfone or polychlorotrifluoroethylene. Although ceramic UF membranes are produced using metal oxides alumina, titania and zirconia in addition, they can be stabilized with aluminum oxide the cerium oxide nanoparticles [6]. The UF method varies depending on the configuration, so it can be used in flat sheet, tubular, capillary/hollow fiber and spiral wound modules [7]. Under the influence of technological development, scientists have come up with new UF membrane materials, that have selective properties, increased permeability, repelling and mechanical toughness for grimy industrial applications [8].

Due to the selective separation property of UF, the field is gaining wider application in biopharmaceuticals, food and beverages, and water and wastewater treatment, among others [9]. In biotechnology, ultrafiltration or UF is being used for different stages of the purification and concentration of proteins such as antibodies, vaccines, enzymes, and amino acids [10]. The UF method is widely used for food and beverage applications; it allows combined concentration, clarification and pasteurization of milk, juices, wines and plant extracts [11]. While UF is increasingly being seen as a pre-treatment step for membrane-based desalination processes, it is important to note that many factors can affect the efficiency of the process [5].

Furthermore, UF membranes have a pivotal part to play in the production of safe drinking water as well as wastewater reuse by removing turbidity, pathogens, viruses and undesirable micropollutants [12], [13]. These results lead to the growth of the global UF market in which the industrialists' expansions and the regulations for water quality improvement get stricter in the coming years. The demand for UF systems has outgrown the industry's capabilities over time and therefore, spurred the researchers to find new solutions through innovations in materials, membrane fabrication process, and process intensification to advance the current technology.

Though a few reviews are available on UF membranes with many others that are focused on theoretical aspects or certain applications, the existing research niche still presents an opportunity. Due to impressive progress being made, there is a need to conduct a systematic review to assess the latest developments and highlight the areas where improvement is required in the case of UF membrane technology. As such, the goal of this statistic review is to show how UF membranes have come back into fashion by giving an objective analysis and future outlook of the latest research findings. The project's scope includes plain UF and advanced membrane synthesis routes, novel membrane materials, module fabrications, performance studies and applications in the last decade. Furthermore, we have furnished a quantitative-statistical assessment of research themes, regional contributions, and institutional productivity which all are objectively supported. Also, these features are used to identify the global revival of UF membrane research and to define directions for future sustainable development of this technology.

2. Historical Development of UF Technology

Ultrafiltration (UF) is a pressure-driven membrane filtration process that involves the separation of solutes from fluids using a semipermeable membrane. In this process the membrane pore size ranges from 1 to 100 nm [16]. UF membranes do the job of strain-away of colloids and macromolecules, bacteria, and, viruses, but the water and low molecular weight solutes are let through [17]. The historical progression of UF technology can be summarized in three main areas: seed stages and baby steps, exploration of UF membrane material development, and highlighting the core innovations in the UF processes.

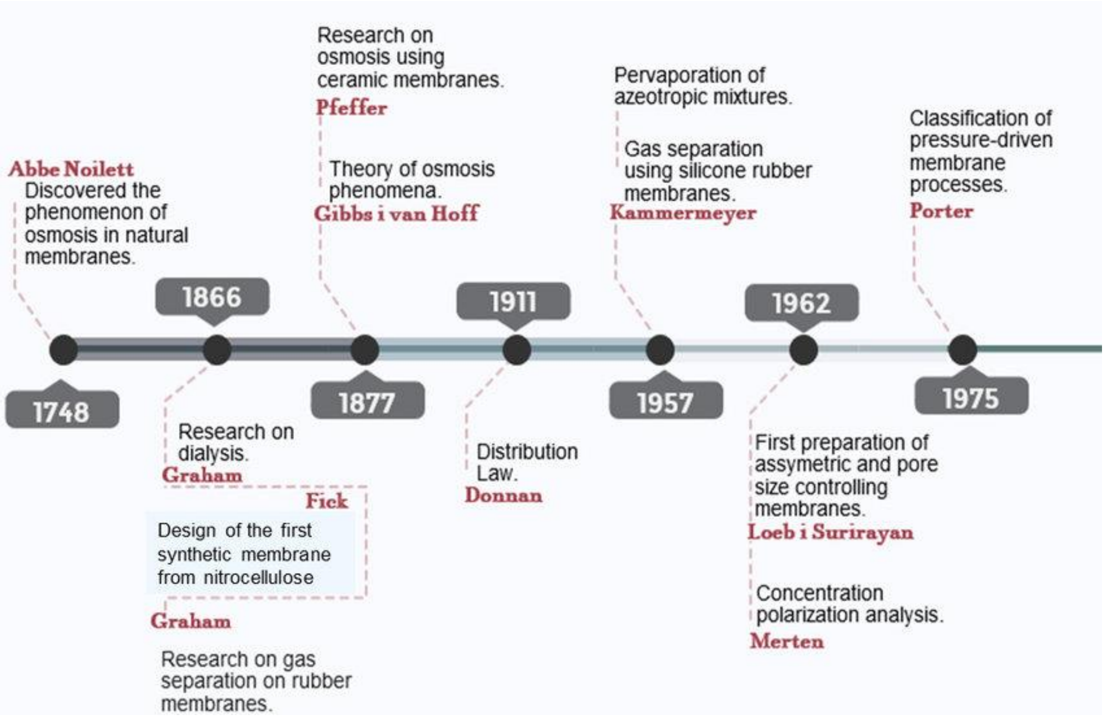

Figure 1. Evolution of UF Membrane Materials [18]

Initial works dealing with this topic became known already in the 18th century when experiments with membranes based on animal bladders were thought to be helpful [19] in Figure 1. Meanwhile, CA membranes with asymmetric structures are considered milestones in primitive UF membranes due to Loeb and Sourirajan's invention in 1960 [20]. This innovation was the result of their creation of polymer solutions that were cast in two layers symmetrically on top of each other to form an asymmetric membrane with a permeability that was more improved than that of the symmetric membrane [21]. Since 1970, vast improvements in the CA casting process for the membranes allowed the operators to employ the first industrial-scale UF for wastewater treatment and protein concentration [22]. Still, the 1970s and 80s brought some other UF milestones, like the commercialization of PAN and PS UF membranes, which have better chemical resistance compared to CA membranes.

The goal of the advancement of UF membrane materials is to improve the selectivity, chemical-thermal stability, and antifouling properties, as well as efficiency. Earlier, membranes were prepared from cellulosic materials like CA which had a very low permeability leading to low chemical and temperature resistance [18]. PAN and PS membranes, by allowing work at harsher environments and higher temperatures [19], have expanded the application area of gas separation and recovery for process industries. Since the 1990s forward the TFC membranes deployed for filtration purposes from polymeric and ceramic materials commingled together have taken over the market [20]. Such tunnels-fining of the top layer with polyamide ultrafiltration (UF) membrane on porous polysulfone supports has increased the UF membrane permeability compared to asymmetric membranes [16].

Researchers have likewise made strides in bioreactor designs, as well as in the process engineering of UF. The grand majority of the early UF systems used the dead-end diffusion model which was associated with several problems including concentration polarization and membrane fouling . In the 1980s when crossflow filtering was introduced, the limits of the batch mode were overcome to an extent making it possible for designers to design continuous UF systems [23]. Crossflow UF coupled with plenty of turbulence promoters, periodic pulsations, and optimized module designs, a process having very high values of efficacies and flux rates were obtained [24]. Moreover, membrane module engineering has evolved from the plate-and-frame type to hollow-fiber and tubular type which are more efficient and effective. Even today, the novel UF process advances focus mostly on the enhancement of module designs and better pre-treatment options to improve the performance of the process and minimize the fouling of the membrane [25].

3. Fundamentals of Ultrafiltration

UF is a membrane separation process that is driven by pressure and utilizes porous membranes to separate solvents, solutes, particles, colloids, and macromolecules of their differing sizes by molecular sieving [26]. The principles and fundamentals of UF separation are the retention of contaminants by the sieving mechanism and membrane pore size. Upon the entry of a solvent, the particles lower than the pores are retained and those beyond the pores are filtered [27]. The average diameters of pores vary from 1-100 nm, which allows the filtration on the microfiltration scale to the nanofiltration. This is the situation where the UF system is capable of isolating big molecules such as proteins from the small solutes.

The structures of UF membranes with pores of different sizes and shapes are considered a key factor that affects membrane separation and flux directly. The membrane can be either symmetric or asymmetric, with a skin layer of a high density being the convenient supporting of a porous sublayer [28]. The practical realization of such membranes is, however, challenging because the separation characteristics are determined by the skin layer and the support provides mechanical strength. Morphology as well as the pore size distribution of the membrane is dependent on the fabrication method and the kind of polymer [29]. Typical building units include a finger-like pore in phase inversion membranes, an intertwined sponge-like channel in the track-etched membrane, and hollow channels. Fabrication parameters such as porosity, pore size, pore distribution, surface roughness, wettability, and chemical resistance are the main parameters to be optimized [30].

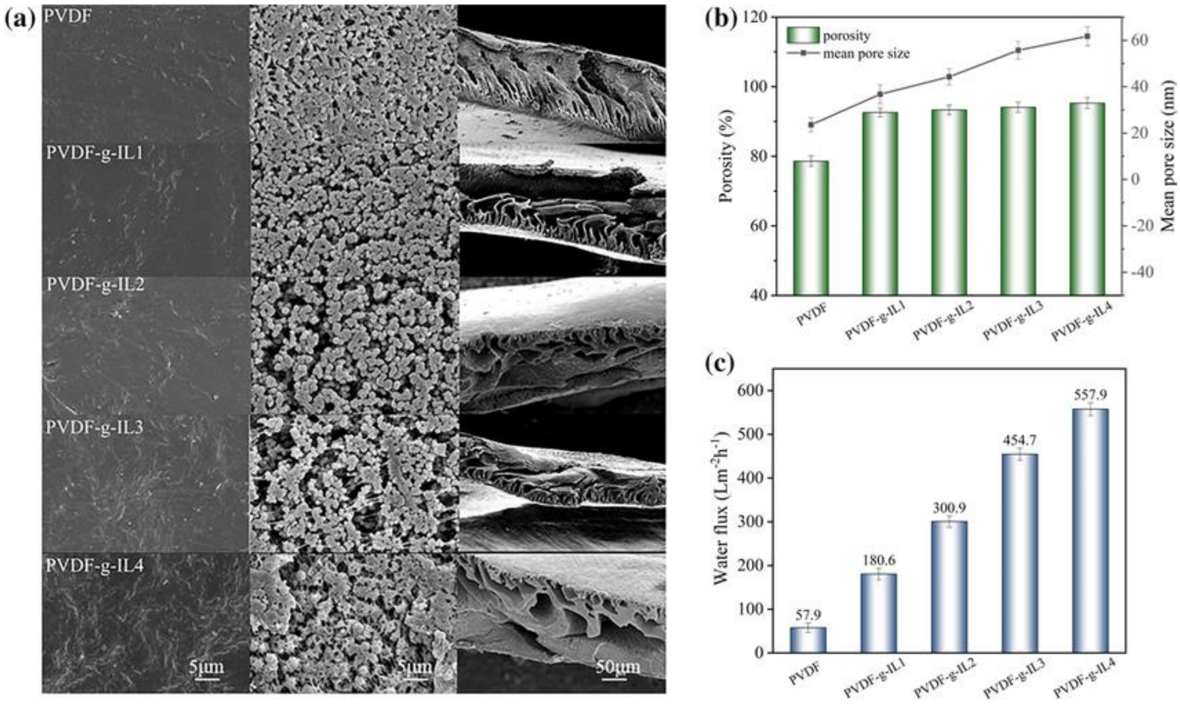

Figure 2. Membrane Morphology and Pore Structure of PVDF [31]

The different factors in the UF systems that are not working are efficiency and output in Figure 2. They are operational conditions [32], membrane features, and characteristics of feed solutions. Crucial to the functioning of the system are the following input variables: transmembrane pressure, crossflow velocity, flow mode (batch vs continuous), temperature, and module assembly [33]. The choice of transmembrane pressure and crossflow velocity can improve separation flux but may create more fouling. Hormone levels increase with elevated temperature which causes rapid growth but may interfere with compound synthesis. Feed and bleed operation has retentate concentrate and low flux average [34]. Characteristics of feed composition including pH, ionic strength solute concentration greatly affect the degree of membranes' charge, solute rejection and fouling [35]. Pre-treatment and membrane cleaning processes are usually very helpful in forecasting up to 90% of the fouling that is expected as well as improving the performance. The overall system efficiency is due to the integral interdependencies of these interacting elements.

In short, the UF disc separation core is based on the membrane porosity structure and filtration permeate stream. Operation and efficacy are controlled by operating parameters, membranes' steric properties and feed solutions' components. New findings see UF being applied to water, food, biotechnology, and other sectors either directly or removing the need for several steps.

4. Types of Ultrafiltration Membranes

Table 1. The characteristics and examples of each type of ultrafiltration membrane

Type of Membrane	Examples
Polymeric Membranes	- Polyethersulfone (PES) - Polyvinylidene fluoride (PVDF) - Polysulfone (PS) - Polyamide (PA)
Ceramic Membranes	- Alumina-based membranes - Zirconia-based membranes - Titania-based membranes
Hybrid Membranes	- Polymer-ceramic composite membranes - Thin film composite membranes (TFC) - Zeolite-incorporated membranes

Membranes are ultrathin barriers of materials that exhibit the capability to differentiate based on physical or chemical differences between chemical species. Polymers comprise a category of membranes called polymeric membranes, ceramics that form another one of such membranes called ceramic membranes, and hybrid membranes are the most used membranes in the industrial sector in Table 1.

Polymeric membranes are synthesized membranes, which are made up of polymer chains that can accommodate pores of different sizes depending on the polymer used and the manufacturing process [37]. Polymers that are used regularly are polyethersulfone (PES), polyvinylidene fluoride (PVDF), polysulfone (PS) and polyamides (PA) [38]. The merits of such materials as polymeric membranes, which are versatile and tunable in the pore size, are to be found in water treatment processes, gas separation, pervaporation and so on as well as membrane bioreactors [39]. The upsides to polymeric membranes are their high permeability, low energy consumption, easy fabrication and affordable cost [40]. On the other hand, polymers include thermal, mechanical and chemical stability problems and defects.

Ceramic membranes, which are made of inorganic materials such as alumina, zirconia, titania, zirconium oxide, and silicon carbide, have gained popularity for numerous filtration and separation applications [41]. They are characterized by exceptional chemical stability and will bear highly astringent conditions such as high temperatures and pressure [42]. Silica and polymer ceramic membranes are robust and have long operating lifetime-enabling applications, including membrane filters in hot gas combustion, membrane reactors in catalytic processes, electrolysis cells, and liquid separation [43]. Nevertheless, the ceramic membranes are the high-priced and tough-in-fracture systems.

Composite membranes comprise polymeric and inorganic hybrids and take advantage of the benefits of both groups in the membranes [44]. Specimens consist of polymer-ceramic composite membranes, thin film composite (TFC) membranes, and zeolite-containing membranes. The justification for the synthesis of advanced membranes is to provide higher selectivity, permeability, temperature endurance, and mechanical strength than that of ordinary homopolymeric membranes [45]. TFC membranes that employ their selective polymeric layer on porous ceramic support are widely applied in the reverse osmosis method of desalination [46]. The thin-film polymer successfully provides selectivity while the ceramic support gives the product the required mechanical strength.

5. Applications of Ultrafiltration

The UF membrane scope has been revived in the recent past, being recommended for a diverse range of industries because of its versatility and high efficiency. In water treatment and desalination, the UF membranes act as a pretreatment for the RO system by removing the particles, the colloids, the viruses and the large organic molecules [47]. Additionally, an inline process protects against membrane fouling contributing to the extended lifespan of the downstream processes. The breakthroughs occurring in nanotechnology and material science have enhanced the UF membrane's properties of control permeability, optimization for selectivity, chemical resistance, and antifouling [48]. New materials such as graphene oxide and biomimetic aquaporin membranes have shown the ability for better water fluxes than the traditional flat sheet UF membranes.

UF serves as a critical tool in food and beverage processing for its applications to clarify, concentrate, and fractionation of products [49]. The ability of UF membranes to aseptically filter the juice of fruit while retaining the substances, responsible for the flavor, is a key feature [50]. Membrane fractionation furthermore enables the purifying and keeping of whey proteins with nutraceutical value obtained from dairy generators [51]. The crossflow UF systems play an energy-saving role, as they can replace the thermal technologies before the milk is cheesed [52]. Nevertheless, bioactive peptides (UF) purified from cheese whey show antimicrobial properties that are alternative to synthetic preserving agents [53].

In the pharmaceutical industry, there are applications of ultrafiltration for the fractionation of antibodies in biotherapeutics production as well as for the isolations of target compounds. Without this virus clearance by the UF, there is no possibility of the biopharmaceutical derivation of cells in culture being safe (8). High molecular weight cutoff UF membranes could be applied for pre-formulation to give diafiltration and buffer exchange requisites [54]. Furthermore, UF is a quick mechanism that enables the recovery of proteins and the purification of extracellular vesicles, for the examination of novel biomarkers from biofluids [55].

In industrial plants, UF has been specifically utilized as a replacement for conventional separations like settling, media filtration and chemical coagulation. Metallurgical customers make use of UF to recycle industrial engraving fluids degraded by tramp oils or sludges [56]. Textile dyeing wastewater and pulp/paper effluents usually contain recalcitrant dyes, lignin and even toxic residuals, which amount to serious pollution by-products that impose a load for tertiary UF processes [57]. Therefore, breakthroughs made lately have given the UF membranes wider coverage philosophies and industries.

6. Performance Evaluation and Characterization Techniques

6.1. Flux and Rejection Rate Measurements

Table 2. Measurement parameters of membrane rates with examples

Measurement Parameter	Examples	Considerations
Flux	- Pure water flux - Flux of model solutes	- Operating pressure and temperature
Rejection Rate	- Rejection of specific solutes	- Molecular weight cut-off (MWCO)
Fouling Rate	- Flux decline over time due to fouling	- Cleaning protocols
Recovery Rate	- Recovery of valuable components from feed stream	- Desired concentration levels

Membrane separation processes like microfiltration, ultrafiltration, nanofiltration, and reverse osmosis have become very important technological options for use in applications like sewage decontamination, concentration and separation of desirables from feed streams, food and beverage processing, and pharmaceutical purification [58-60] in Table 2. Certain parameters as very important to stop and observe such as unit operations efficiency resulting in flux, rejection rate, fouling rate and recovery rate [61]. Flux is a parameter that describes the volumetric flow rate of the permeate fluid permeate unit membrane area and is usually reported as LMH (liters per square meter per hour) [62]. It shows the dynamic permeability of the membrane and it is associated with the operating pressure, temperature and feed characteristics, in addition to membrane properties [63]. A high rate of flux is salient but it has to be in conjunction with a high efficiency of extraction. Rates of rejection denote the fraction of solutes that the membrane can reject, shown as a percent [64]. This not only reveals the capacity of the membrane to distinguish components based on characteristics like molecular weight, shape, and charge but also exhibits the membrane's ability to permit the flow of materials across it [65]. Rejection rates depend on the membrane cut-off that rates the molecular weight as well as feed characteristics [66]. By the fouling rate, we mean the gradual accumulation of material on the membrane surface as it operates. This rate is measured by the way the flux continually declines. And also, fouling decreases the throughput and this frequently prompts the cleaning process to raise the flux [67]. The recoverable rate should be considered essential for applications that are dedicated to preserving and concentrating permeate. It will define the % of feed being removed via permeate (12%). The essence of these key parameters performance, membrane selection and subsequent optimization of operating conditions can be achieved when applications are the target [68].

6.2. Membrane Fouling and Cleaning Strategies

Table 3. Overview of various membrane fouling and cleaning strategies in ultrafiltration, along with examples and descriptions of each strategy

Strategy	Description	Examples
Backwashing	Reversing the flow direction across the membrane to dislodge and remove accumulated foulants.	- Hydraulic backwashing - Air scouring
Chemical Cleaning	Using specific cleaning agents to dissolve or disperse foulants, organic deposits, or mineral scales.	- Acid cleaning (e.g., citric acid) - Alkaline cleaning

Strategy	Description	Examples
Mechanical Scrubbing	Physical agitation or scrubbing to mechanically remove fouling layers from the membrane surface.	- Brush cleaning - Sponge scrubbing
Biological Cleaning	Employing enzymes or microorganisms to degrade organic foulants, biofilms, or microbial growth.	- Enzymatic cleaning - Bioaugmentation
Enhanced Cleaning Methods	Utilizing advanced techniques such as ultrasonication, ozone treatment, or electrochemical cleaning.	- Ultrasonic cleaning - Ozone cleaning

The membrane fouling reduces the operation time and the lifespan of the membrane; thus, creative cleaning and maintenance are required. Membrane (foulants) cleaning strategies are commonly used either using physical, chemical, and biological methods. The hydraulic backwash mechanizes the reverse flow to scour the fouling sand, while the airflows are entered into pores to perform the shear forces [69,70]. In contrast to chemical cleaning, which takes into account the specific characteristics of the foulant and membrane, the chemical solution is designed by the fouling type and membrane properties in Table 3. Acidic solutions do the best when it comes to the removal of mineral attachments, while alkaline solutions are more efficient in dissolving organic soil layers [71]. EPS is the main purpose of the bioball wall decomposition through an enzymatic activity [72]. In line with this, the technology utilized behind current practices has developed and now incorporates ultrasonication, ozone generation and electrolysis as means of improving its efficiency [73]. Oxide and degrade organic foulants in the ozone process, while ultrasonic waves and electrolytic reactions can produce free radicals and localized high temperatures effectively to speed up the foulant removal process [74-77]. Using a combination of cleaning methods, such as the backwashing of physical and the chemical enhancement of chemical contaminations to synergistically remove the complex ones will be another strategy [78]. Ongoing research will be required in the future to incorporate cleaning protocols specific to different membrane process variants and types of wastewater.

7. Future Perspectives and Outlook

Ultrafiltration (UF) membranes witnessed a coming back or reemergence over the last decade and this was due to the new generation of materials that have been developed which are made possible by the advancement in manufacturing technologies, hence, enhanced physical properties like permeability, selectivity, fouling resistance, and chemical stability [79]. Nevertheless, this technological advancement needs further improvement.

Another main issue consists of the formation of the next UF membranes possessing both high permeability and selectivity [80,81]. The most important work has been carried out, however, in dramatically enhancement of the permeability but there have been no significant attempts to improve the selectivity. It is important to maximize both of their characteristics in different application areas. Moreover, Computational modeling and Machine learning can aid in the discovery of UF membrane materials and structures, which can be used to accelerate the development of the same [82].

Scaling, organic deposits and biofilm development result in the deterioration of efficiency as time goes by. Modern antifouling strategies with nanotechnology and fouling-discouraged coatings are offering new possibilities to substantially increase antifouling activity [83]. Backpulsing and chemically enhanced backwashing also require adaptations to reduce membrane replacement costs [84]. Fabrication methods of membranes embedded into small, easy-to-operate and lazy-cuts stand a chance to decentralize water treatment systems by locating at the points where water is drunk and eliminating the labor-intensive and electricity-driven standard ones in developing communities and remote areas [85-87]. Among these, innovative ways of making UF membranes have already shown some promise and can become the next field for exciting research. Nanoarchitecturing includes layer-by-layer nanoassembling, surface graft polymerization, incorporation of stimuli-responsive polymers, and thin-film nanocomposite membranes with nanomaterial fillers [88]. Understanding their performance structural relationships will be critical to designing the next-generation materials [89]. A considerable research area encompasses recycle and reuse of UF membranes that could cover a great number of possible cases and cost reductions [90]. Future work on broader mechanical stability, selective layer replacements, and membrane constituent recycling can widen the list of possible applications.

The increasing global demand for clean water, shifting environmental regulations, especially in the food, pharmaceutical and semiconductor industries plus the use of water reuse will be the major reasons for the wider use of UF technology because of its efficiency in energy, space compactness and ability to select the contaminants [72]. The implementation of automatic and sensor integration can also be done and this can lower the labor costs. Decisive achievements, that reduce lifecycle influence using longer membrane lifespan, decreased sedimentation, and reusability will be in favor of ecological conservation. In addition to this, UF treatment can be recycled from the wastewater, which will also ensure space utilization than the conventional treatment process, thus preserving land resources [91]. The reality is a chillingly similar tunnel, riddled with spikes and detritus. However, the gloomy veneer is soon replaced by a breathtakingly beautiful orchestra of colorful birds chirping in the distance. However, these persistent challenges are just some of the terrains that give continued opportunities for the membrane community to come up with improved materials, processes and systems.

Conclusion

The adoption of ultrafiltration has today become quite common in industries that have specific purification needs such as those that want to obtain solutions of specific macromolecular components and remove impurities from highly concentrated solutions containing particles or microbes. The production of membranes of nanofibers and graphene oxide has now driven the state-of-the-art limit in selectivity while module designs and cross-flow modes of operation have features for continuous and high-efficiency operation. Usages cross various areas such as wastewater treatment, food and beverage processing, drug purification, and so on. Yet, fouling problems are still among the top issues that are faced by membrane bioreactors, the cleaning solutions using physical scouring, chemical solutions, and enzymatic deterioration are being applied to correct this problem. Among the prospects to be explored are fouling-resistance membranes and process innovations that will increase the application of ultrafiltration. Nevertheless, it remains one of the fundamental parts of more critical systems that are dependent on the sterile filtration of process fluids and selective fractionation of valuable products, among others. The use of ultrafiltration in many industrial and bioprocess applications will be enhanced leading to wider application across industries that value particles, bacteria, and molecular components being separated reliably and efficiently.

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