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Review article

Modelling and optimization of membrane process for removal of biologics (pathogens) from water and wastewater: Current perspectives and challenges

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ABSTRACT

As one of the 17 sustainable development goals, the United Nations (UN) has prioritized “clean water and sanitation” (Goal 6) to reduce the discharge of emerging pollutants and disease-causing agents into the environment. Contamination of water by pathogenic microorganisms and their existence in treated water is a global public health concern. Under natural conditions, water is frequently prone to contamination by invasive microorganisms, such as bacteria, viruses, and protozoa. This circumstance has therefore highlighted the critical need for research techniques to prevent, treat, and get rid of pathogens in wastewater. Membrane systems have emerged as one of the effective ways of removing contaminants from water and wastewater However, few research studies have examined the synergistic or conflicting effects of operating conditions on newly developing contaminants found in wastewater. Therefore, the efficient, dependable, and expeditious examination of the pathogens in the intricate wastewater matrix remains a significant obstacle. As far as it can be ascertained, much attention has not recently been given to optimizing membrane processes to develop optimal operation design as related to pathogen removal from water and wastewater. Therefore, this state-of-the-art review aims to discuss the current trends in removing pathogens from wastewater by membrane techniques. In addition, conventional techniques of treating pathogenic-containing water and wastewater and their shortcomings were briefly discussed. Furthermore, derived mathematical models suitable for modelling, simulation, and control of membrane technologies for pathogens removal are highlighted. In conclusion, the challenges facing membrane technologies for removing pathogens were extensively discussed, and future outlooks/perspectives on optimizing and modelling membrane processes are recommended.

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1. Introduction

In numerous arid places across the globe, the need for irrigation water in agriculture intermittently or consistently surpasses the existing water supplies [1]. The increase in population exacerbates the scarcity of water, the intensification of agricultural activities, the degradation of soils, and climate change, resulting in reduced precipitation [2,3]. To address this issue, the practice of using wastewater for irrigation is becoming more prevalent, as it allows for the utilization of its significant nutrient content [1]. Insufficiently processed or untreated wastewater is a problem, mostly because of its high levels of salt and heavy metals [4]. However, the greatest concern is the presence of pathogens derived from human and animal waste. Pathogens (also referred to as biologics in this review paper) have the potential to infect crops and endanger the health of farmers, farmers' assistants, and consumers; hence, wastewater for irrigation requires water free of contaminants [5]. Hence, it is imperative to subject wastewater to pathogen elimination treatment, alongside primary treatment to eliminate Chemical and Biological Oxygen Demand (COD/BOD), salt, and metals, before its utilization in agriculture [6]. Pathogens found in human and animal waste, such as bacteria, viruses, and parasites, have the potential to cause various infections and diseases. Inadequate sanitation practices, including improper disposal of waste and lack of access to clean water and sanitation facilities, can contribute to the spread of these pathogens [7]. This risk is not limited to specific countries or regions but can be found globally, especially in areas with poor sanitation infrastructure and practices. Countries with greater potential for poor sanitation problems include Sub-Saharan Africa, South Asia, and conflict-affected regions [8]. Dominant gaps in the sanitation system are education and awareness, infrastructure, resource allocation, and policy and governance. Addressing these gaps in sanitation management requires a multifaceted approach, including investment in infrastructure, education, policy reform, and international cooperation to ensure access to safe sanitation for all [9].

The United Nations (UN) has prioritized the objective of "clean water and sanitation" (Goal 6) as part of its efforts to reduce the discharge of emerging contaminants and pathogens into the environment. Target 6.3 highlighted the need to "improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally" by 2030 [10].

Urban wastewater and contaminated surface water are mainly composed of microbial pathogens that must be decreased to a standardized level to mitigate potential risks to human health [4,11]. According to virus recognition and treatment outcomes, successfully eradicating viruses with a one-step treatment would be difficult [12]. To remove viral pathogens as effectively as possible, it has been proposed that the primary (physical), secondary (biological), and tertiary (physicochemical) processes be integrated with wastewater treatment, which is feasible with modern treatment techniques [13]. The main goal of the wastewater treatment process is to eliminate pathogens from wastewater to minimize health hazards and prevent the transmission of diseases [14]. It is becoming more and more important to treat wastewater for pathogen removal considering the present coronavirus epidemic caused by SARS-CoV-2 and the urgent health risk posed by pathogens in wastewater [14–17]. To ensure safe wastewater disposal and reuse, this review will highlight cutting-edge and practical current technology in comparison to traditional approaches.

There are several conventional methods for removing pathogens from wastewater, including coagulation [18], filtration [19], chlorination [20], activated sludge treatment process [21], and anaerobic digestion [22]. Nevertheless, there are several environmental issues with current disinfection methods, including the use of hazardous chemicals and the production of toxic by-products. For example, the implementation of coagulation and sedimentation techniques for pathogen disinfection requires the utilization of chemical coagulants such as iron and aluminium ions [23,24]. The process of disinfecting pathogens using coagulation and sedimentation procedures can produce detrimental by-products in the form of sludge, which may harbour viable and active pathogens. Thus, the World Health Organization emphasized the necessity of treating wastewater in properly built and efficiently operated centralized wastewater treatment facilities [12]. To efficiently combat waterborne disease transmission, the current wastewater treatment system may necessitate enhancement and the incorporation of further pretreatment or post-treatment measures. The use of membrane technology in wastewater treatment has become widely popular worldwide due to its exceptional separation efficiency, cost-effectiveness, relatively small footprint, environmental sustainability, and user-friendly operation and maintenance [25,26]. Based on the size exclusion principle, a membrane is a selective layer that permits some components to pass through while blocking unwanted constituents [23]. Researchers have focused a lot of attention on the removal of pathogens using advanced membrane technologies, such as membrane distillations, nanocomposite membranes, membrane bioreactors, and photocatalytic membrane

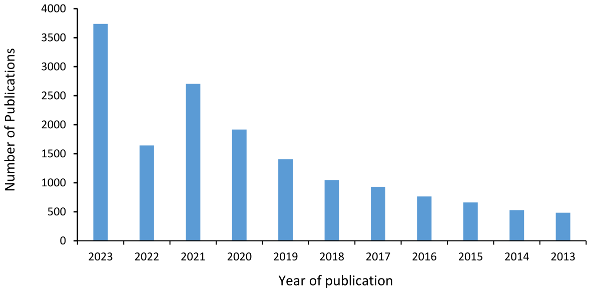

Fig. 1. ScienceDirect web (Membrane, pollutant/pathogens). Source: https://www.sciencedirect.com/search?qs=pathogens%2Fpollutants%2Fmembrane. Assessed on 21st December 2023.

reactors, in addition to traditional membrane filtration techniques [27,28]. Advanced membrane technologies provide the ability to combine filtration properties with other functionalities, hence enhancing the properties of the original membrane [29].

The application of membrane processes for pathogens removal has increased in recent years. Fig. 1 shows the trend of the publication of water pollutant-pathogen-related articles in the literature in the past ten years. It can be observed that there is a progressive increase in the study of the topic as indicated on Science Direct Web with input search "Membrane-pollutant-pathogens".

However, more investigations are required to ensure control, water quality improvement, cost-effectiveness, tracking and planning, and an all-inclusive comprehension of real-time resource loss in a membrane system used for water and wastewater treatment. Additionally, minimal research was found in the literature on the synergistic or conflicting effects of operational conditions on several emerging contaminants inherently existing in wastewater [24]. Hence, the proficient, dependable, and swift analysis of pathogens within the intricate wastewater matrix remains a notable challenge. Furthermore, there is a deficiency in a comprehensive assessment that considers the environmental, economic, and technical factors of membrane processes for wastewater treatment [30]. Moreover, there has been insufficient focus on optimizing membrane processes to develop an optimal operational design, as related to pathogens or wastewater treatment generally. In addition, there is a lack of comprehensive literature reporting on the use of artificial intelligence (AI) approaches in the exploration of membrane processes performance for water and wastewater treatment within the context of Industrial Revolution 4.0 (4IR) (especially in terms of water flux and membrane fouling) [31,32]. The interaction of the membrane and other micropollutants in the wastewater treatment plants can also be predicted using artificial intelligence techniques.

Hence, this paper aims to briefly highlight the conventional techniques of removing pathogens from wastewater and thoroughly examine newly reported membrane technology used to reduce pathogens in wastewater treatment systems. Also, current trends in removing pathogens by membrane techniques, optimization, and modelling of the membrane process are highlighted. The challenges facing membrane technologies for removing pathogens were extensively discussed, and future outlooks/perspectives on optimizing and modelling membrane processes are recommended.

2. Biologics in wastewater

2.1. Pathogens

Contaminated surface water has frequently been discovered to be the breeding ground for numerous viruses, including Norovirus, Rotavirus, Adenovirus, Poliovirus, and Coxsackievirus, to mention a few. Similarly, the discovery of *E. Coli*, faecal coliforms, and oocysts like Giardia proves that the surface water is contaminated [33]. Drinking water contaminated with these microbes can have serious health effects, including hepatitis, diarrhea, meningitis, polio, encephalitis, and more [34]. Hence, it is imperative to efficiently control waterborne pathogens in wastewater to ensure human well-being and save the environment. Pathogens in this context encompass specific species of viruses, bacteria, and protozoa [35]. The effectiveness of wastewater treatment processes for pathogen removal is measured using a concept called 'log removal values' (LRVs), applied to each collective 'group' of pathogens (i.e., LRV for viruses, LRV for bacteria, etc.). A log removal value (LRV) measures the ability of treatment processes to remove pathogenic microorganisms [24]. LRVs are calculated by applying the logarithm function to the ratio of pathogen content in the influent and effluent water of a treatment process, as demonstrated in Equation (1).

$$\text{LRV} = Log_{10}\left(\frac{Influent\ pathogen\ concentration}{Effluent\ pathogen\ concentration}\right) \tag{1}$$

An LRV (Log Reduction Value) of 1 corresponds to a 90 % elimination of a certain pathogen, an LRV of 2 corresponds to a 99 % elimination, an LRV of 3 corresponds to a 99.9 % elimination, and so forth [24]. Fig. 2 shows a multiple barrier reuse scheme for removing pathogens from wastewater, using the LRV. Table 1 presents a list of significant waterborne pathogens and the diseases they cause. Subsequent subsections provide detailed information on the pathogens present in water and wastewater to give a better understanding of the review paper.

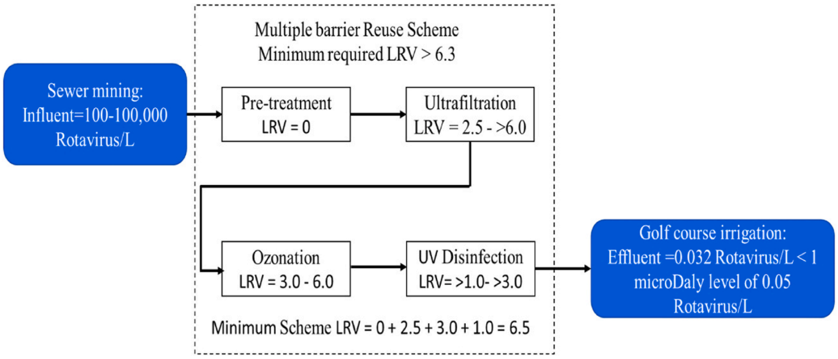

Fig. 2. Multiple barrier reuse scheme for removal of pathogens from wastewater. (Adapted and modified from Water Research Australia, [35]).

Table 1
Important pathogens and the diseases caused by them [33].

Type of pathogen	Name of pathogen	Diseased caused	Observations/Sources
Bacteria	Salmonella spp.	Typhoid fever	Human excreta, sewage, agricultural run-off
	Shigella spp.	Shigellosis	Careless handling of feces, poor water quality
	Pathogenic *Escherichia coli*	Gastroenteritis, Diarrheal	Contamination of fecal matter
	Campylobacter spp.	Gastroenteritis	Sewage and fecal matter
	Vibrio cholerae	Cholera	Human excreta
	Yersinia esterocolitica	Gastroenteritis	Human and animal excreta
Virus	Rotaviruses	Diarrhea	Water contaminated with human feces
	Enteric adenoviruses	Gastroenteritis	Human excreta
	Calciviruses	Gastrointestinal illness	Human excreta
	Astroviruses	Gastroenteritis	Sewage contaminated water
	Small round viruses	Gastroenteritis	Human feces
	Hepatitis A virus	Hepatitis A	Human feces
	Hepatitis A virus	Hepatitis A	Sewage contaminated water
Helminth	*Ascaris lumbricoides*	Ascariasis	Human excreta
Protozoa	Entamoeba histolytica	Amebiasis	Human excreta
	Giardia lamblia	Giardiasis	Water contaminated with human feces
	Cryptosporidium parvum	Cryptosporidiosis	Water contaminated with human and animal feces

2.1.1. *Virus*

Evidence shows that the quantity and variety of harmful viruses in wastewater correlate with the distribution of infections among people. Some of the most common human pathogenic viruses spread through water media include adenovirus (HAdV), rotavirus (RoV), hepatitis A virus (HAV), and other intestinal viruses such as noroviruses (NoV), coxsackievirus, echovirus, reovirus, and astrovirus [33]. Children and adults contract watery illnesses like diarrhea from enteric viruses, also linked to other disease outbreaks [16]. Numerous deadly diseases, such as hepatitis, gastroenteritis, and respiratory disorders, are caused mainly by viruses. The SARS-CoV-2, a novel coronavirus, is responsible for the COVID-19 pandemic, which has been designated as a global health emergency by the World Health Organisation (WHO) [15,36].

In less than 20 years, the world is currently dealing with its third coronavirus-related pandemic [37]. The human respiratory and gastrointestinal systems are both impacted by the SARS-CoV-2 virus. The virus has been found in wastewater treatment plants, sewage, and human waste [36]. Given that, it has already been established that numerous species of mammals may contract the disease, hence it has the potential to become a pandemic [38]. Since the virus can be detected in sewage even before symptoms appear in the local population, wastewater-based epidemiology should be developed to identify infection clusters of the first wave as well as to identify a possible second or subsequent wave [17]. Techniques for removing viruses from wastewater must be used to stop the virus from spreading to the environment and causing a pandemic. Size is crucial for membrane-based treatment procedures since it establishes the

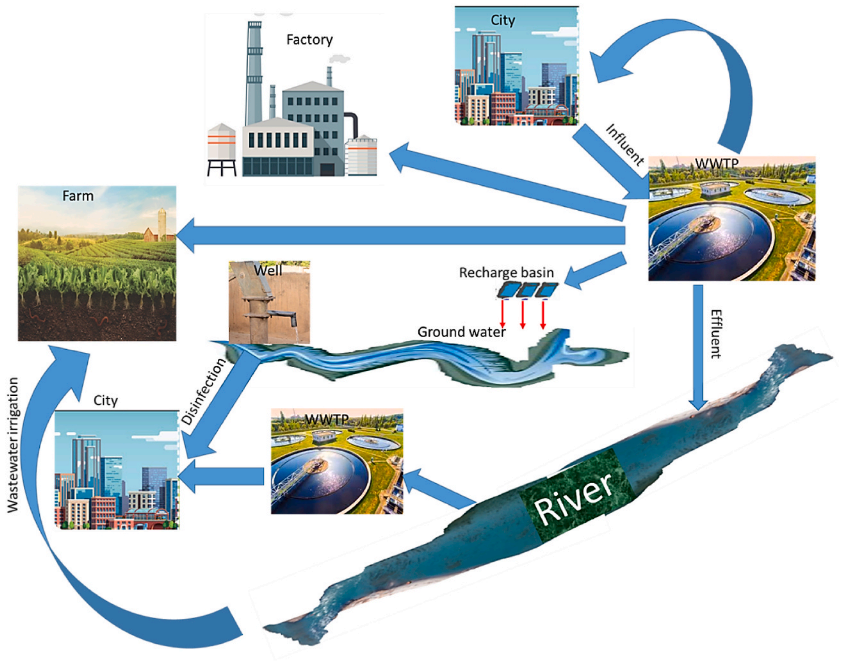

Fig. 3. Transmission of the virus through faecal matter into main water streams (Adapted from Lahrich et al. [36]).

membrane's maximal pore size, which needs to be chosen to eliminate the virus particles. Bar-On and colleagues presented recent findings indicating that the size of SARS-CoV-2 is around 100 nm [39]. SARS-CoV-2 can persist on surfaces, spread through direct touch, and be transmitted by aerosols released by infected individuals when sneezing or coughing [17]. Additionally, SARS-CoV-2 RNA has been detected in human feces.

Furthermore, Medema et al. [40] conducted a study in the Netherlands to investigate the existence of COVID-19 RNA in six specific sites. The detection commenced six days before the first cases were reported. Similarly, Randazzo et al. [41] in Spain and Wu et al. [42] in the USA identified the presence of COVID-19 RNA in wastewater, even in areas with a low frequency of the virus. La Rosa et al. [43] documented the identification of COVID-19 in raw sewage in Italy. This prompts inquiry into the existence of SARS-CoV-2 in the aquatic environment. COVID-19, being a global pandemic, has affected 215 countries, including those with advanced wastewater treatment facilities as well as poor nations that release untreated wastewater directly into water bodies. Several publications have reported the existence of live SARS-CoV-2 virus or RNA in aquatic habitats [17,44–46]. Sewage and wastewater treatment plants (WTT) are a key point of possible transmission for the virus, and WTT can have a crucial function in identifying and managing the spread of SARS-CoV-2, as shown in Fig. 3. According to Medema et al. [40], sewage tracking is an effective method for monitoring the spread of SARS-CoV-2 in the population. It can detect the presence of the virus even before symptoms are reported by patients. Given the economic ramifications of the current pandemic, significant endeavours must be made to enhance worldwide wastewater treatment, particularly in terms of eliminating or neutralizing viral contamination. Conventional methods of treating wastewater have demonstrated efficacy in eliminating viral infections through various mechanisms, hence posing a substantial risk to public health [15].

2.1.2. Bacteria

Bacteria are the most prevalent pathogenic microbes in wastewater. These bacteria fall into two main groups: opportunistic bacteria and enteropathogenic bacteria. One of the wastewater's most prevalent bacterial illnesses is digestive illness [47]. These include dysentery (induced by numerous *Shigella* and *Salmonella* species) and diarrhea (e.g., cholera induced by *Vibrio cholera* and *salmonelliosis* triggered by various *Salmonella* species). Paratyphoid and typhoid fever are other prevalent illnesses (induced by *Salmonella species*) [48]. Additionally, wastewaters contain not only the known pathogens but also a variety of opportunistic pathogens, such as *Pseudomonas and Streptococcus,* which are bacteria that, given the right circumstances, can cause infections and sickness, usually in the elderly, very young, and immune–compromised people [49].

Bacteria are just as dangerous as viruses when present in drinking water [50]. It is commonly known that wastewater serves as a breeding ground for a variety of pathogenic bacteria, including *Streptococcus faecalis*, faecal coliforms, and *Bacillus subtilis* [34]. Wang et al. [51] reported the presence of a variety of opportunistic pathogens, such as *Mycobacterium avium*, *Legionella pneumophila, amoeba,* and *Pseudomonas aeruginosa*, in water from secondary water supply systems. However, most opportunistic pathogens are bacteria that can withstand chlorine. Therefore, water filtration and a healthy water supply are vital because infectious diseases can spread through water and raise mortality rates. A few waterborne illnesses, including cholera, typhoid, dysentery, etc., can be attributed to bacteria. This is especially true in poorer nations and those where poor sanitation practices lead to increased pollution. As a result, people are forced to drink this contaminated water because of a lack of safe drinking water and suffer from these waterborne illnesses [11].

Thus, plans for safe drinking water must be made to end such hopeless circumstances. Numerous research groups have considered the efficacy of membrane filtration in eliminating microorganisms from drinking water after observing similar circumstances worldwide [34]. The subject of science and technology related to membrane filtration is advancing rapidly due to its highly effective pathogen removal capabilities. Additionally, the membrane filtration technique offers several advantages over other conventional techniques and improved efficiency, which has helped manage pathogens in wastewater [52].

2.2. Sources and conventional methods of pathogens removal (bacteria and viruses) from water and wastewater

Microorganisms are widely recognized for their several advantageous functions in wastewater systems. They are particularly helpful in lowering the amounts of sludge and sewage effluent in both on-site wastewater treatment systems, including septic tanks and wastewater treatment plants (WWTPs) [53]. Nevertheless, research has revealed that a few unusual species are harmful and have fuelled the spread of multiple epidemics of waterborne illnesses. The most often applied bacteria evidence of wastewater contamination is coliform bacteria, particularly *Escherichia coli*. Likewise, human feces, especially those from diseased individuals, are one of the primary sources of pathogens in wastewater [16]. Researchers have recently reported traces of this virus in various wastewater, including secondary-treated wastewater, municipal sewage, river water, and medical wastewater [11]. The enteric viruses that cause the most common infections are rotavirus, norovirus, hepatitis A virus (HAV), human adenoviruses, and enteroviruses. In wealthy and developing countries, these infections are linked to several waterborne illnesses, such as conjunctivitis, severe gastroenteritis, and respiratory diseases [54]. Osuolale and Okoh [53] assessed the presence of viruses and bacteria in various wastewater treatment facilities. In every wastewater treatment plant, faecal coliform bacteria and *E. coli* were found, but no relationship between the enteric bacteria and viruses under investigation was found. The discovery of rotavirus in effluent samples released into surface waterways emphasizes the importance of determining whether residential water sources are contaminated with viruses [36]. Therefore, to eliminate the undesirable effects of consuming contaminated surface water, it is crucial to provide drinking water free of pathogens [34].

The presence of a disease-causing microbe in drinking water poses a significant risk to human health [55,56]. The poisoning of drinking water has resulted in disease epidemics in both developing and developed countries, leading to a significant number of fatalities globally [57]. The implementation of physicochemical approaches can effectively manage numerous aquatic illnesses.

Contemporary water purification methods typically integrate physical and chemical treatment technology. Conventional approaches for controlling harmful microorganisms in drinking water systems include thermal disinfection [58], application of ozone, chlorine, and UV radiation [59], or utilization of a membrane filtration system [60].

Although the current treatment procedures for certain harmful microorganisms are successful, they are expensive and can produce excessive secondary pollutants that are more dangerous than the original substance. Therefore, it is necessary to develop better approaches. After undergoing chlorine treatment, the development of trihalomethanes at a concentration of 160 ppb can be observed, which poses major risks to human health [61].

Conversely, the additional compounds themselves may pose a risk that exceeds the permissible dosage. The primary approach for reducing microbial contamination in drinking water involves chemical treatment techniques that focus on oxidizing the organic constituents of living cells. Nevertheless, the application of a specific disinfection procedure may not be equally feasible in eradicating all pathogenic microorganisms present in drinking water, hence highlighting the limitations of the method. Viruses, in general, are less prone to routinely used chemical disinfection methods [61].

So far, the conversation has centered around the need for drinking water standards that require very effective removal of pathogens. In many instances, it may be adequate to achieve a lower level of pathogen elimination, particularly when the objective is to shield vulnerable ecosystems from pathogen pollution by depending on following natural purifying processes. As an illustration, in cases where waste liquid needs to be released into specific locations identified by the European Bathing Waters Directive (2006/07/EC), and the categorization is determined by the measured levels of environmental E. Coli and enterococci concentrations, operators of wastewater treatment facilities may need to restrict the release of harmful microorganisms into bodies of water. The requirements may vary depending on whether the release is intended for inland or coastal water.

Likewise, the recently established Shellfish (growing) Waters Directive (2006/113/EC) provides specific instructions regarding the permissible levels of coliform bacteria in shellfish collected from certain regions. In other locations, the United States Environmental Protection Agency (USEPA) has revised guidelines for improved surface water treatment rules, with a primary goal of safeguarding groundwater resources against the spread of disease-causing pathogens originating from infiltrating surface waters. Operators must assess the effectiveness of their treatment systems in removing pathogens if the incoming wastewater is contaminated [24,62].

2.2.1. Treatment of pathogens: removal procedures and inactivation (disinfection) processes

Treatment of pathogens is conducted using two methods: removal procedures and inactivation (disinfection) processes. These processes are ideally included in a comprehensive “multiple barrier” treatment strategy that aims to safeguard water sources by using water of the highest initial quality, followed by effective removal of pathogens, subsequent disinfection, and final protection measures to prevent contamination in the water distribution system [63]. Both traditional technology and more recent therapeutic approaches are used in pathogen eradication procedures. Pre-treatment with coarse filters (gravel, sand, etc.) or other techniques usually lowers gross turbidity (pathogen populations are usually high on particles), and it is particularly useful in lowering concentrations of algae and protozoa (LRV 2–3 is easily attained) [64]. Primary pathogen elimination can be achieved through uncomplicated settlement in storage reservoirs or via bank filtration. Storage not only facilitates settlement but also provides a period for the eradication of germs and viruses outside their host environment. Nevertheless, these kinds of basic treatment systems are rarely enough to achieve the high levels of pathogen eradication necessary for acceptable health protection.

Pretreatment is commonly enhanced by employing flocculation, coagulation, and subsequent sedimentation as part of the clarification treatment process. An instance of this is when successful coagulation depends on precise administration and blending of often fluctuating influent loads, as well as efficient and well-regulated sludge extraction. Moreover, the process of eliminating viruses can differ greatly depending on the species, and the extent of this difference (up to a maximum of LRV 2) is also affected by the type of coagulant used. High-rate clarifiers are typically used to obtain higher LRVs (Log Reduction Values) for major pathogen groups. However, it is important to exercise caution when dealing with problem areas involving the removal of algae to avoid disturbing algal cells and triggering the release of toxins [24]. Dissolved air flotation is a viable substitute for eliminating algae (with a log reduction value of 1–2 for many species) and is also an effective method for removing Cryptosporidium oocysts (with a log reduction value of 2–2.6). In certain situations, gravel and slow sand filtration may be the sole economically viable methods for eliminating pathogens. These systems can be very effective depending on flow rates, media size, uniformity, and filter bed depth. Tests have revealed LRVs ranging up to 5. Simultaneously, practical knowledge gained in the United States shows that sand filters can achieve a total coliform LRV of up to 2.3 and effectively remove Giardia (with an LRV of around 4), especially once microbiological films have formed on the filter media. Nevertheless, the ability to treat water can be limited, and the effectiveness of removing pathogens can vary significantly; specifically, the removal of Cryptosporidium has consistently demonstrated subpar results (LRV often <0.5) [24].

Pathogen disinfection, or inactivation, is the second crucial method. To summarise, oxidation heat and UV treatments are employed for pathogen control. Oxidation reacts with the organic composition of the pathogen, heat eliminates pathogens by surpassing their thermal limits, and UV destroys the genetic material of the cell, hence impeding reproduction [51]. The efficiency of oxidative disinfection varies depending on the species and is determined by the duration and dosage of contact under constant conditions [5]. Several oxidants, such as chlorine gas, monochloramine, sodium hypochlorite, and chlorine dioxide, are chlorine-based. Ozone is among the various options. While a comprehensive analysis is not included in this article, it is important to note that the effectiveness of disinfection, often measured as the needed time-dose products to achieve a specific Log Reduction Value (LRV), can differ greatly depending on the type of oxidant used and can be affected by factors such as water turbidity, pH, and temperature. Operators should consider several factors when selecting appropriate oxidants, such as the plant’s resistance, the safety of workers who may come into contact with these dangerous and corrosive compounds, the necessary quantities, and the storage and stability properties of the oxidants [5,12].

As a result of the shortcomings of some of these conventional techniques of removing pathogens from wastewater, researchers have been drawn to the utilization of emergent membrane technology for the effective removal of pathogens. Therefore, various advanced membrane techniques for removing pathogens from water and wastewater are extensively discussed, and recent studies are provided. Numerous research groups have investigated the efficacy of membrane filtration in eliminating microorganisms from drinking water after noticing similar circumstances worldwide. In addition to offering greater efficiency over conventional techniques, membrane filtration technology has several other benefits, as highlighted in the subsequent section.

3. Membrane filtration technologies for the removal of pathogens (bacteria and viruses) from wastewater

The application of membrane-based microbial decontamination techniques in wastewater treatment has experienced significant progress in the water purification sector [65,66]. The advantages of membrane-based techniques compared to conventional treatment methods can be summarized as follows: (i) the production of water with consistent properties, (ii) the rapid and effective removal of pathogens that are resistant to chemicals, (iii) the prevention of bacterial regrowth, (iv) the minimal presence of residual chemical hazards, and (v) the promising ability to decontaminate polluted water to meet standard quality levels. Membrane filtration is now often used in both newly constructed water treatment plants and the upgrading of existing plants. The advantage of membrane filtration over other traditional methods for treating wastewater and retaining bacteria has already been demonstrated [34]. The mechanism that governs the application of membranes for the removal of biologics is very critical in understanding the separation process.

3.1. Mechanisms of membrane separation

Nanofiltration (NF) is an intricate process that relies on the micro-hydrodynamic and interfacial phenomena taking place at the surface of the membrane and within its nanopores. The rejection of NF membranes may be ascribed to steric, dielectric, and transport phenomena [67]. The membrane charge arises from the dissociation of ionizable groups located on the membrane surface and within the membrane pore structure [68]. These groups can be either acidic, basic or a combination of both, depending on the individual materials utilized in their creation [47]. The dissociation of these surface groups is significantly affected by the pH of the fluid they come into contact with. The surface chemistry of the membrane is amphoteric, meaning that it can display an isoelectric point at a particular pH. NF membranes possess a limited ion-exchange capacity, in addition to their ionizable surface groups.

The membrane charge may occasionally be slightly altered by ions from the contacting solution that adsorb to the membrane surface [69]. Because of the phenomenon, electrostatic repulsion or attraction depends on the ion valence and the fixed charge of the membrane, which can change depending on the localized ionic environment. The concept of dielectric exclusion is not well comprehended, and there are two primary conflicting hypotheses on the precise nature of the interaction [70]. Both exclusion mechanisms occur because of the highly limited spatial confinement and nano-scale dimensions in NF membrane separations, and they are essentially exclusion phenomena based on charge. Solutes in free solution encounter drag forces from the solvent as it flows through the restricted pore structure [33]. The solute's mobility inside this restricted area is significantly influenced by the immediate

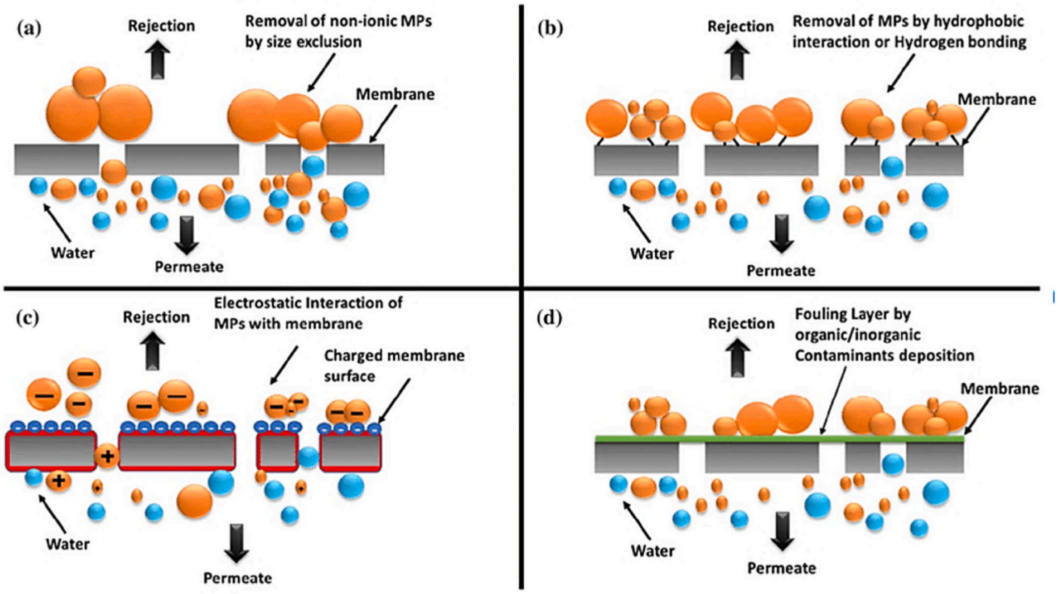

Fig. 4. Mechanism of membrane separation for wastewater treatment (a) size exclusion, (b) hydrophobicity, (c) electrostatic interaction and (d) adsorption. Reprinted with permission from Khanzada et al. [74].

surroundings, resulting in impeded solute transport. The obstruction of transportation can be described as a combination of convective and diffusive factors that contribute to the entire transportation process.

The membrane processes' ability to exclude particles based on size is crucial for achieving high pathogen removal efficiency, as depicted in Fig. 4. A membrane's suitability for eliminating all harmful microorganisms cannot be guaranteed solely based on its defined pore size. In some circumstances, over time, the membrane may experience reduced effectiveness in removing pathogens due to the occurrence of breaches, salt deposition, and the creation of biofilm in the filter being used [71]. As a result, the overall performance of the filtration technology is constrained. However, the elimination of harmful microorganisms through membrane filtration is influenced by various parameters, such as the surface properties [72] and the duration of the pathogen's contact with the membrane [73]. The lack of precise measurement technologies and the extremely small size of the NF active layer have hindered a comprehensive understanding of the physical structure and electrical properties of natural NF membranes. Consequently, there is ongoing uncertainty and significant debate regarding the separation mechanisms and the disputed role of dielectric exclusion [67,70].

3.2. Advanced membrane technologies for removal of pathogens (viruses and bacteria) from wastewater

The membrane filtration technologies are divided into concentration–driven membrane filtration, electrical–driven membrane filtration, and pressure–driven membrane filtration, as depicted in Fig. 5 [75]. Various technologies, including those that are already developed, can effectively implement a pathogen eradication approach that is suitable for its intended purpose. Table 2 presents the virus removal range and the strengths and weaknesses of each technology. The different membrane techniques used for treating pathogenic-containing water are presented in Table 3.

The findings of this study indicate that membrane filtration and disinfection technologies have the potential to effectively treat wastewater and drinking water carrying viruses throughout a broad spectrum of LRVs (0.5–7 LRVs and 0.09–8 LRVs, respectively). From an alternative standpoint, the integration of membrane-based separation and other technologies has the potential to leverage their distinct advantages and overcome their individual limitations. Soon, tertiary treatment methods such as membrane filtration and disinfection technology will be essential. The inactivation of viruses by disinfectants can be influenced by the presence of organic matter and inorganic ions [76]. Therefore, in certain instances, it may be required to separate membranes before disinfection. Ultrafiltration (UF) and membrane filtration (MF) membranes are typically efficient in preventing the entry of protozoa and bacteria, but their ability to eliminate viruses is limited due to their small dimensions. Research has indicated that a combination of MF-UV and a photocatalytic membrane in a hybrid process was more efficient (LRV $= 5.0 \pm 0.7$) in eliminating and rendering bacteriophage P22 inactive compared to either MF/UV disinfection alone or MF-UV with a non-photocatalytic membrane [77].

Kwarciak-Kozlowska and Wlodarczyk [82] conducted a recent assessment on the use of reverse osmosis for treating waterborne infections. Their description encompassed the various categories of waterborne pathogens, which can be classified into three distinct groups: protozoans (ranging from 5 to 100 μm), bacteria (measuring 0.5–1.0 μm), and viruses (measuring 0.01–0.1 μm). Additionally, they outlined the specifications for materials used in reverse osmosis membranes. They stated that reverse osmosis is rarely employed for pathogen removal in water, despite being one of the procedures recognized by the EPA for achieving log removals exceeding 6. This is because reverse osmosis is commonly used with a pretreatment system, such as ultrafiltration, to decrease the presence of foulants that could disrupt the reverse osmosis process. Nevertheless, reverse osmosis (RO) can be effectively utilized in conjunction with an appropriate pretreatment method to eliminate particle matter, and subsequently, in a post-treatment process to fully eliminate any residual contaminants [83].

While individual wastewater treatment technologies have shown satisfactory performance, hybrid technologies have shown the

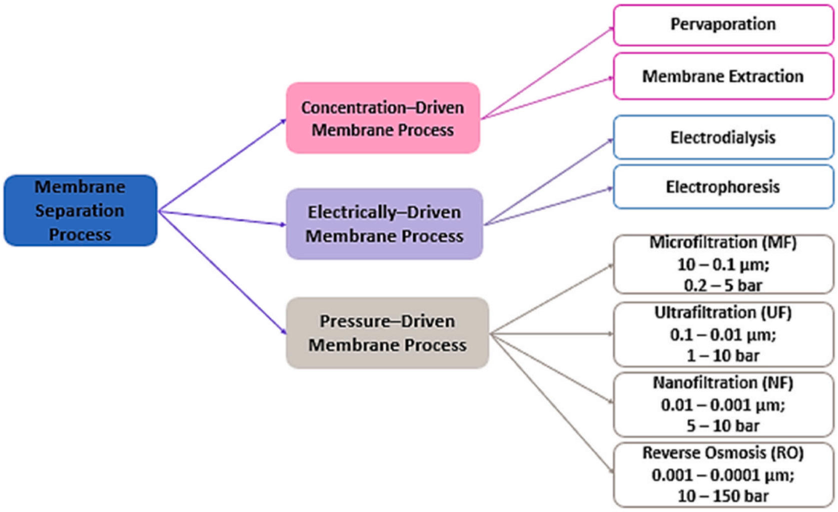

Fig. 5. Classification of membrane separation process for wastewater treatment (Adapted and modified from Suhalim et al. [75]).

Table 2
Virus removal range and the strengths and weaknesses of each technology [24].

Process	Removal (LRVs)	Major function mechanism	Strength	Weakness
MBR	1.4–7.1	Attachment of virus to mixed liquor solids; retention by membrane; retention by membrane cake layer; inactivation of viruses by enzyme	High removal efficiency; high flux and less space demand	Incomplete removal of dissolved organic matters
Microfiltration	0.7–4.6	Adsorption largely onto membrane surface or within its pores; follow by size exclusion	High permeability; low pressure-driven process	Low removal effect; health risk potential for humans
Ultrafiltration	0.5–5.9	The virus can be retained by the membrane and attached to its surface or absorbed within its pores.	High flux and permeability; low energy cost and effective removal of high molecular weight matter	High capital investment and operation; removal efficiency is unstable
Nanofiltration/ reverse osmosis	4.1–7	Size exclusion; Electrostatic interactions	High performance, security, and reliability, dedicated removal of enveloped and nonenveloped viruses based only on size exclusion	High requirements for influent quality

Table 3
Different membrane techniques used for pathogenic-containing water treatment.

Membrane technology	Pathogen	Wastewater source	Findings	Reference
Ultrafiltration	Bacteriophage MS2	Synthetic wastewater	Membranes clouded by soluble microbial products had higher MS2 removal and permeability loss, which may be a reliable indicator of virus removal.	[78]
Nanofiltration	*Escherichia coli*	Medical Wastewater	Log elimination greater than 4 was observed for the membrane bioreactor combined with NF.	[79]
Reverse Osmosis	Adenovirus, Polyomavirus, Rotaviruses	Sewage wastewater	RO systems showed increased efficacy in eliminating the viruses.	[80]
Microfiltration	*Staphylococcus aureus* *Escherichia coli*	Raw water	With 100 % rejection of the pathogen, the membrane composed of 7 % limestone, 83 % kaolin, and 10 % bentonite, demonstrated the best performance.	[50]
Hybrid UV-C/ Microfiltration	*Escherichia coli*, *Enterococcus faecalis*, *Candida albicans*	Urban wastewater	A hybrid UV-C/microfiltration system generated a synergistic effect between UV-C and filtration, which led to the death of 96–98 % of the eliminated microorganisms.	[81]
Ultrafiltration with UV pretreatment	*Legionella* spp., *Legionella pneumophila*, *Mycobacterium* spp., *Acanthameoba* spp.	Secondary water supply	The pathogens in the water remained unidentified after UV-UF treatment, and the quantitative gene evaluation showed that UV pretreatment decreased the number of microbial genes linked to infectious and metabolic illnesses.	[51]

potential to enhance treatment performance, as emphasized in the subsequent section.

3.3. *Advanced/hybrid membrane technologies for removal of pathogens in water and wastewater*

Reclaimed water (i.e., reused advanced-treated wastewater) offers an alternative water resource. Efficient pathogen removal using advanced wastewater treatment processes is vital to mitigate the health hazards linked to reclaimed water use [84]. The advantages and disadvantages of sophisticated tertiary treatments for wastewater polishing have recently been the subject of several review studies, the majority of which have focused on the technological elements of the treatments. For example, NEREUS COST Action specialists examined ozonation, activated carbon adsorption, chemical disinfectants, UV radiation, advanced oxidation processes, and membrane filtration while analyzing the best available technologies for water reuse for crop irrigation [12]. The expert panel concludes that reducing the emission of compounds of developing concern and antibiotic-resistant microbes cannot be achieved with a single sophisticated treatment technique. Luo et al. examined various tertiary systems, including coagulation-flocculation, activated carbon adsorption, advanced oxidation processes, nanofiltration, reverse osmosis, and membrane bioreactors, to determine the removal efficiency of the chosen micropollutants in 14 different countries and regions [85]. Rizzo et al. conducted an analysis comparing consolidated and novel tertiary treatment approaches. They found that the absence of comparison research between these two groups makes it difficult to choose the most appropriate and cost-effective strategy for treating developing pollutants [86].

Over the past ten years, advances in technology have made membrane filtration a feasible method for treating wastewater by increasing its robustness, dependability, and affordability. In drinking water applications, the primary goal is to achieve the highest possible removal efficiency, which is often accomplished using a multiple-barrier strategy. Efficient implementation and maintenance of basic media filtration might be a valuable component of this strategy. While modern ultrafiltration (UF) or reverse osmosis (RO) technologies provide a strong alternative, it is still necessary to deactivate microorganisms to establish and sustain disinfection. Both MF (microfiltration) and UF (ultrafiltration) are successful methods for removing pathogens in common wastewater discharge applications, while also achieving other water treatment goals [87].

Research studies seldom prioritize the investigation of pathogen elimination through Nanofiltration (NF) phases, as an ultrafiltration unit is typically employed beforehand to prevent the creation of biofilm. Ultrafiltration membranes effectively prevent the passage of bacteria, viruses, and organic micropollutants. However, only nanofiltration (NF) and reverse osmosis (RO) membranes are capable of adequately retaining these substances [88]. Fig. 6 depicts two complimentary pressure-driven membrane technologies, the membrane filtration technologies [75]. These methodologies are coupled because they each have inherent limits and, as a result, do not provide adequate performance monitoring when used separately.

Likewise, Fujioka et al. [89] conducted a study to verify the disparity in bacterial movement through the reverse osmosis (RO) membrane element, both before and after the O-ring seal was attached. This was accomplished by quantifying bacterial populations throughout the treatment of ultrafiltration-treated wastewater. When the O-ring seal was not utilized alongside membrane A element, the bacterial counts in the permeate increased from an initial value of 23 counts per mL to 310 counts per mL when the reverse osmosis (RO) input was changed from RO-filtered tap water to ultrafiltration (UF)-treated wastewater (Fig. 7). With the O-ring seal bonded, membrane A had a far lower degree of bacterial count rise. Bacterial counts in RO permeate reduced with time in both situations. According to the decline in bacterial counts in RO feed, there was a corresponding decrease in bacterial counts in RO permeate. The reduced bacterial counts in the RO feed were most likely a result of the bacteria adhering to the surfaces of the RO membrane and feed spacers, as the tests were conducted by recirculating the RO feed and permeate using a closed-loop RO system.

Wang et al. [51] examined the impact of UV pretreatment of wastewater to minimize ultrafiltration biofouling in a secondary water supply system. To eradicate harmful bacteria from water, a combined UV–ultrafiltration technology was used. The results of the investigation indicated that the UV pretreatment inactivated the pathogenic bacteria in the presence of residual chlorine and that the bacteria were effectively eliminated by ultrafiltration. Compared to the untreated ultrafiltration membrane, the UV pretreatment of the membrane revealed tiny pores, and visible fissures, and figure a lower roughness and bacterial flow proportion.

Bui and colleagues conducted a comprehensive evaluation of advanced treatment methods for the removal of micropollutants. The assessment included a limited discussion of environmental factors and focused on a selection of tertiary treatments, namely adsorption, ozonation, UV/H_2O_2, membrane processes, and membrane bioreactors [90]. Membrane filtration has demonstrated superior germ elimination effectiveness compared to traditional methods, while also requiring less time for operation and occupying a smaller space [91].

According to Chen et al. [24], the UF and NF processes are the most effective methods for eliminating pathogens in polluted wastewater. The UF process achieved removal values (LRVs) ranging from 0.5 to 5.9, while the NF process achieved removal values ranging from 4.1 to 7.0. In comparison, the MF process only achieved pathogen removal values ranging from 0.7 to 4.6. Nevertheless, MF exhibits superior water permeability and fouling mitigation capabilities because of its larger pore size [92].

Forés et al. [5] evaluated the application of electrochemical-enhanced oxidation to remove pathogens from wastewater, and the technique was reported to be effective for water disinfection. The electrochemical process inactivated viruses, bacteria, protozoa, and bacteriophages in wastewater, thus making the treated water suitable for irrigation. Botti et al. [93] applied electrifying secondary settlers for pathogen removal from wastewater in another study. The study conducted by Lee et al. [84] thoroughly investigated the effectiveness of viral elimination using coagulation followed by ultrafiltration (UF) in the treatment of drinking water. Nevertheless, the effectiveness of employing secondary processed effluent from wastewater treatment plants (WWTP) for wastewater reclamation objectives remains uncertain. Therefore, the application of nanotechnology is expected to address this issue and eliminate pathogenic microbes from wastewater.

There are many ways to improve water and wastewater treatment through the use of hybrid/integrated processes. This can be achieved by combining different types of membranes (such as MF and/or UF with NF and/or RO) and incorporating various membrane techniques before or after the usual separation methods. Additionally, conventional separation techniques like precipitation, coagulation, adsorption, ion exchange, and biological treatment can also be employed. The integrated methods may employ the combination

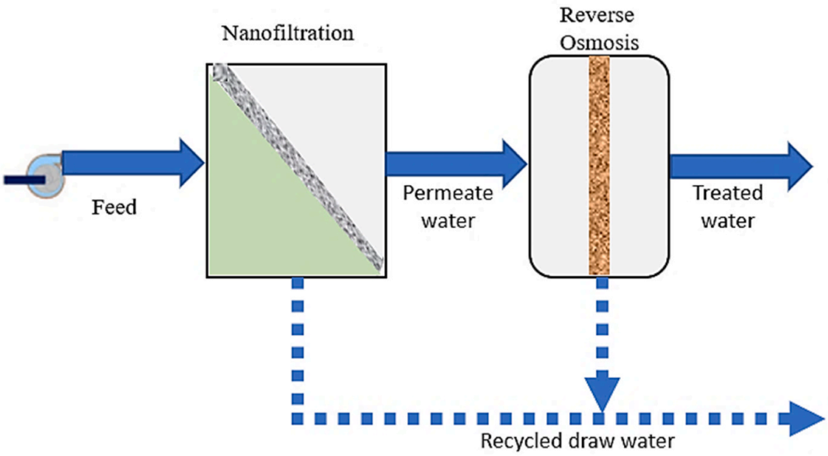

Fig. 6. Complimentary NF and RO hybrid system for removal of pathogens from water.

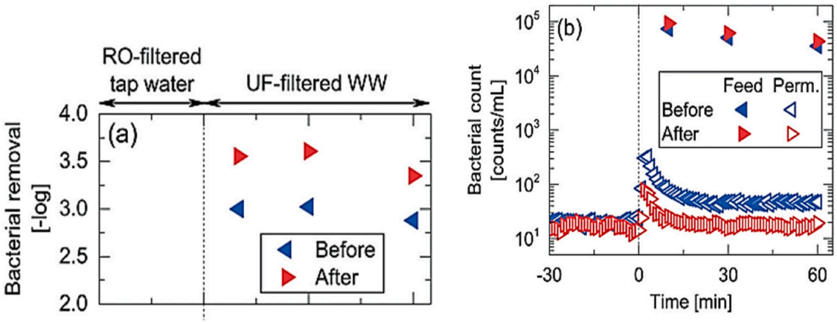

Fig. 7. (a) Elimination of bacteria and (b) quantification of bacterial populations during the treatment of tap water filtered by reverse osmosis (RO) and wastewater treated with ultrafiltration (UF) utilizing membrane A component (before and after bonding). Reprint with permission from Fujioka et al. [89].

of activated carbon with a low-pressure membrane process, specifically microfiltration and ultrafiltration. The development of hybrid technology has been crucial in achieving low or zero liquid discharge (ZLD) for the treatment of industrial waste wastewater. Fig. 8 depicts the adsorption-membrane integrated system. Future improvements required in the membrane-based techniques for the removal of pathogens in water and wastewater are provided in the next section.

3.3.1. Future improvements in the membrane-based technologies

Utilizing a combination of various membrane-based technologies shows a promising approach as an alternative to conventional methods for eradicating pathogenic microbes that are resistant to chemical disinfection. This approach also effectively prevents the regrowth of bacteria species and removes harmful chemicals, resulting in water purification that meets standard criteria. Under real-world circumstances, the NF technology may not pose a significant obstacle to human pathogens, such as bacteria and viruses [95]. In addition, the functional efficiency of nanofiltration technology for pathogen removal may decrease with time due to the development of breaches in the membrane. This highlights the importance of continuously evaluating the integrity of the membrane. The membrane breaches typically occur as a result of chemical or biological degradation processes, aging, scratches induced by particulate matter, membrane fouling, detachment of membrane layers, incorrect fitting of connectors, O-rings, and other factors. In addition to the factors listed above, membrane defects can also occur during the production operations of the membrane. Therefore, conducting regular tests to assess the integrity of the membrane at precise intervals would aid in preserving the effectiveness of any water purification procedure that relies on membranes, particularly in eliminating harmful microorganisms commonly found in drinking water. Impregnating the membrane with silver nanoparticles may be an effective strategy to prevent membrane biofouling, a significant issue that reduces the overall efficiency of the separation process [51,71]. Nevertheless, there is a possibility of the loaded nanoparticles leaking into the permeate to a certain degree.

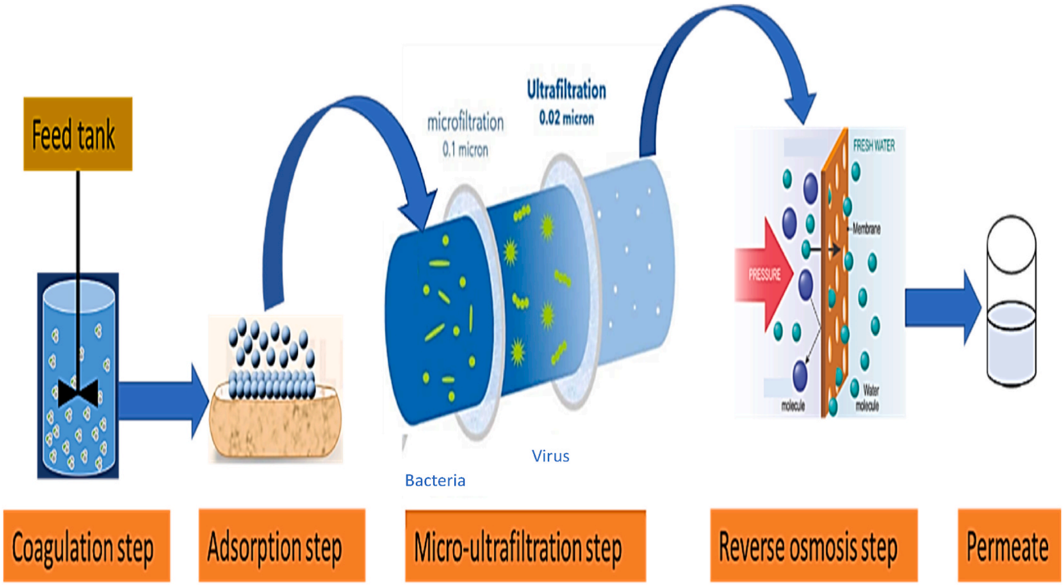

Fig. 8. Adsorption-membrane hybrid system (Adapted from Khan and Boddu [94]).

Continued progress in this area would undoubtedly enhance the membrane's separation efficiency. Industrial-scale use is advisable for disinfecting drinking water that is polluted with several waterborne human diseases. It is crucial to have a well-designed wastewater treatment plant that takes into account all aspects of sustainability, including economic, environmental, and social dimensions. One way to accomplish this is by employing systematic models that integrate conceptual and mathematical tools.

The objective of wastewater management is to implement measures for environmental preservation, taking into account economic and social considerations [96]. Before constructing and installing a wastewater treatment plant (WWTP), it is crucial to address the topic of the cost associated with implementing the most effective technology that meets environmental criteria for discharged water, while also fostering community development and gaining public acceptability. The decision-maker endeavours to identify the optimal choice with minimal cost. However, the selection of the most suitable wastewater treatment plant (WWTP) is not solely a matter of economics. It is crucial to consider other factors, such as environmental and social considerations, during the decision-making process [97]. Integrating a comprehensive evaluation of sustainability, encompassing the economic, environmental, and social aspects, can result in enhanced wastewater management.

Urgent attention is required for the optimization of membrane processes to develop optimal operation design as related to pathogen removal from water and wastewater. Mathematical models suitable for modelling, simulation, and control of membrane technologies for pathogens removal will be extensively discussed in the next subsections of this review paper.

4. Mathematical modelling and optimization of the membrane-based process for removal of biologics from wastewater

The choice of membrane-based technology for wastewater treatment depends on the necessary level of purity, mobility, and the process's economics. Among the many factors that can impact the efficiency of membrane-based technologies are feed water characteristics, filtration time, feed flow rate, permeated vapor pressure, and feed temperature. While membrane-based processes for water treatment are characterized as energy-intensive, they receive special recognition because of the many advantages they exhibit over conventional methods [98]. The wastewater treatment objective is setting up a process that maximizes economic benefit and lasting stable operation at optimum conditions [38], which can be achieved through process integration and optimization.

Mathematical modelling and optimization have become an integral part of membrane-based processes for wastewater treatment as the need to predict a system's performance has become essential. Hence, it is a vital tool for sustainability, as it helps to realize both economic and environmental advantages associated with wastewater treatment [30]. Mathematical modelling and optimization are critical in providing valuable data for process control and plant design, playing a vital role in predictions used for experimental designs and the estimation of non-measurable parameters [31]. Models are helpful for process monitoring and studying factors that affect performance characteristics for each process to find the correct configuration for the membrane system [99,100].

A framework for the design of wastewater treatment and reuse networks was presented by Quaglia et al. [101]. Within a computer-aided environment, the framework took into account engineering expertise, problem analysis tools, and optimization techniques. To minimize both the total annualized cost and the wastewater discharge rate, Sueviriyapan et al. [102] concentrated on the methodical design of a water management system for retrofitting wastewater treatment networks of an existing industrial process. Furthermore, an integrated framework for the best network selection of a WWTP architecture was described by Castillo et al. [103]. The integrated methodology merges the use of knowledge-based and superstructure-based optimization techniques to minimize the overall annualized cost. The authors assert that the integration of both instruments leads to the attainment of reciprocal benefit and synergy.

Start Several theoretical methodologies exist for forecasting the membrane efficiency of suspension solutions. These methodologies rely on suitable models, including boundary layer adsorption, mass transfer (film theory), osmotic pressure, gel-polarization, surface transport models, shear-induced diffusion, inertial lift, and Brownian diffusion [104]. Furthermore, apart from the intricate nature of the mathematical equations employed, each of these models possesses numerous constraints: (i) They require experimental data to determine the input parameters. (ii) None of the approaches can accurately explain the complete flux-time behaviour of the process; they often only forecast the steady or pseudo-steady-state flux. (iii) Each method is only applicable to specific feeds under specific conditions. Traditional modelling faces substantial challenges in accurately predicting membrane performance due to many key constraints. These include the diversity of feed composition, the absence of reliable fouling prediction models, and the intricate characteristics of the membrane surface and membrane interactions. The mathematical models are intricate, costly, and necessitate thorough process expertise. Hence, the lack of sufficient descriptions of the governing physicochemical events hinders the accurate prediction of membrane performance.

Over the past few decades, significant advancements have been made in developing modelling techniques to support wastewater treatment systems [105]. There has been widespread use of models for the modelling, optimization, and prediction of the removal of different contaminants from wastewater. For instance, Lotfi et al. accurately predicted the removal of conventional pollutants like BOD and COD from wastewater using a hybrid linear and nonlinear model [106]. Response surface methodology (RSM) and artificial neural networks (ANNs) were employed by Vakili et al. to maximize the removal of organic micropollutants [107]. Hence, the next section briefly explores the optimization and modelling methodologies to supplement and augment the effectiveness of biologics elimination procedures.

4.1. Modelling and optimization approaches

The following are the modelling and optimization techniques for water treatment; Computational Fluid Dynamics (CFD) facilitates the comprehensive examination of fluid flow patterns, mass transport, and concentration distributions within membrane systems through the utilization of simulations [108]. The integration of computational fluid dynamics (CFD) with membrane modelling enables researchers to enhance flow topologies, develop efficient membrane modules, and forecast the influence of operating conditions on the efficiency of biologics removal. This methodology offers significant contributions to the understanding of flow dynamics and aids in the identification of regions susceptible to fouling or concentration polarization, hence allowing the formulation of methods to address these concerns [109].

Natural Algorithms (GA) are optimization algorithms that draw inspiration from the principles of natural selection and genetics. Within the realm of membrane technology for the removal of biologics, genetic algorithms (GA) can be utilized to enhance the characteristics of the membrane, including the distribution of pore sizes, surface charge, and material composition. This optimization aims to maximize the effectiveness of separation and minimize the likelihood of fouling. Through the iterative process of refining membrane designs using performance data, genetic algorithms (GA) can uncover optimal solutions that may not be readily evident using conventional trial-and-error methods [110]. The primary goal of GA is to apply Darwinian theory-inspired evolution to find the best possible solution to engineering challenges. In a hybrid system, GA can be used as an optimization tool with another machine language to extract mathematical models and determine the best model for a given system [105].

Response Surface Methodology (RSM) is a statistical methodology employed for modelling and optimizing intricate processes that involve numerous variables. Within the realm of membrane technology, Response Surface Methodology (RSM) can be utilized to methodically examine the impacts of several variables, including operating pressure, feed concentration, pH, and temperature, on the efficacy of biologics removal. Researchers can discover optimal process conditions and construct prediction models to guide process optimization and scale-up efforts by fitting response surfaces to experimental data [111].

Hybrid modelling approaches use the integration of various modelling tools, including artificial neural networks (ANN), computational fluid dynamics (CFD), and empirical correlations, to effectively represent the combined impacts of numerous elements on the processes involved in the removal of biologics. Hybrid models can enhance the accuracy of predictions and insights into complicated phenomena, such as membrane fouling dynamics, transport phenomena, and process optimization, by using various modelling approaches. These integrated methodologies capitalize on the respective advantages of each modelling tool to address constraints and improve the accuracy of predictions [112].

Machine learning (ML) ensemble techniques, including Random Forests, Gradient Boosting Machines, and Ensemble Neural Networks, have the potential to enhance the resilience and generalization capabilities of prediction models in the context of biologics removal applications. Ensemble approaches reduce the danger of overfitting and improve model accuracy by combining predictions from numerous base models, especially when the data is noisy or constrained. These methodologies provide a robust structure for constructing prognostic models that can efficiently steer decision-making in bioprocessing protocols [113]. The trend factors of the support vector machine (SVM) and random forest (RF) techniques were high. Support Vector Machine (SVM) is a machine learning technique that is particularly effective when dealing with tiny amounts of data. It is built on a strong theoretical framework and offers the benefits of a straightforward algorithm and high resilience. Random Forest (RF) is a comprehensive technique that uses decision trees to effectively manage non-linear data and mitigate the issue of overfitting. Furthermore, Random Forest (RF) is effective at mitigating erroneous prediction outcomes arising from irregular and multidimensional data, making it one of the most powerful artificial intelligence (AI) algorithms [114]. Support Vector Machines (SVM) and Random Forest (RF) have demonstrated superior performance compared to Artificial Neural Networks (ANNs) in certain experiments. For example, Hossain et al. obtained better predictions for microbial removal from wastewater using support vector regression (SVR) than with RSM and multilayer perceptron ANN. In addition, a genetic algorithm (GA) was hybridized with the models generated by SVR to maximize the removal efficiency under optimal conditions [115].

Fuzzy logic has the benefit of employing approximate reasoning. Nevertheless, a drawback of this approach is the complexity involved in creating and adjusting the fuzzy membership functions (MFs) and rules, which do not possess a proficient learning power. The integration of neural networks, fuzzy logic, and evolutionary algorithms enables one to use their respective advantages and address their limitations [110].

Artificial neural networks (ANN), as a data-driven technique, use a learning algorithm to establish relationships between variables (input and outputs) [116]. Focus has recently shifted to artificial intelligence-based modelling techniques such as ANN because of their preciseness and ability to effectively predict the efficiency of membrane-based processes. Their applications in environmental engineering and other fields of study are also promising [117]. This will be extensively discussed shortly in the review paper. There are many recent advances in the modelling of biologics removal from wastewater using membrane processes.

4.1.1. *Recent advances in the modelling of removal of biologics using membrane processes*

A novel technique utilizing laccase immobilized on ceramic membranes was previously developed to break down antibiotics in wastewater [118]. This study has focused on assessing the economic implications of this novel enzymatic decontamination method. The calculations were derived from prior modelling and simulations of actual-scale processes for the breakdown of tetracycline in effluents from municipal, hospital, and industrial wastewater treatment plants. A cost estimation model, created for ceramic membranes used in petrochemical wastewater treatment, was modified for the proposed enzymatic technology. It was then used to conduct an economic viability analysis of various designed processes. The goal was to determine the competitiveness of this new technology in comparison to alternative decontamination methods [118]. Fouling is one of the main obstacles confronting membrane technology. Therefore, understanding modelling approaches that could address this issue is crucial.

The conventional modelling methodologies employed to investigate the fouling phenomena often require a comprehensive comprehension of the membrane material, foulant contents, feedwater characteristics, and hydrodynamic features [119]. For instance, researchers have examined the impact of foulant material and its qualities on membrane fouling by theoretical analysis. They have also proposed the ideal timing for backwashing by utilizing numerical or analytical solutions derived from physical models [120]. Nevertheless, the majority of these parameters pose challenges in terms of comprehensive characterization or modelling, particularly when dealing with pilot-scale operations where it is not possible to manipulate variables independently. Alternatively, a data-driven modelling technique can utilize extensive datasets derived from contemporary monitoring systems, employing advanced statistical inference analysis. The use of modelling techniques such as linear regression, artificial neural networks (ANN), and random forest (RF) regression has been documented in environmental research focusing on membrane technology and water/wastewater treatment [119, 121].

Furthermore, conventional modelling methods tackle the issue by employing a comprehensive comprehension of the intricate fouling phenomena from a physical and chemical perspective. The study conducted by Zhang et al. [122] involved the collection of a substantial volume of data from a pilot-scale ultrafiltration membrane system used to treat wasted filter backwash water at a water treatment plant. Continuous monitoring is conducted for environmental factors and operating parameters, such as temperature, hydraulic pressure, water turbidity, and so on. The study aimed to uncover the concealed nonlinear connections between these variables using data-driven approaches, without constructing a process model based on fundamental principles. Machine learning technologies are employed to establish a correlation between environmental variables, dynamic parameters, the efficacy of foulant removal by backwashing, and the accelerated rate of foulant accumulation. The predictive accuracy is evaluated by comparing it to regression models, such as linear regression, artificial neural networks, and random forests. The fouling dynamics are modelled using data and this model is subsequently utilized for optimization purposes. Specifically, the time of the backwashing sequence is optimized by employing methods from stochastic dynamic programming, as described by Cogan et al. [120]. The efficiency of backwash performance is evaluated by comparing it with experimental data obtained through a fixed interval sequence. The comparison reveals that the optimized schedule is more efficient, cost-effective, and results in lower membrane resistance. The project implemented a comprehensive workflow encompassing data processing, model development, and operational optimization. The sole prerequisite for implementing the methodology is the acquisition of operational data to discern the dynamics of the membrane. The technology described in the research has great promise for being used in large-scale ultrafiltration applications. It may effectively reduce energy consumption and extend the lifespan of the membrane [122].

Aside from ultrafiltration applications, microfiltration membranes are being increasingly utilized in disinfection operations, namely, to remove viruses from water to reuse municipal wastewater [110]. Prior studies have shown the efficacy of microfiltration membranes in eliminating viruses from water. Madaeni and Kurdian [110] demonstrated the effectiveness of fuzzy logic in modelling and simulating the dead-end microfiltration process for the removal of infectious bovine rhinotracheitis (IBR) and Foot-and-mouth disease (FMD) viruses from water. The membrane's performance was assessed by experimentally determining its key

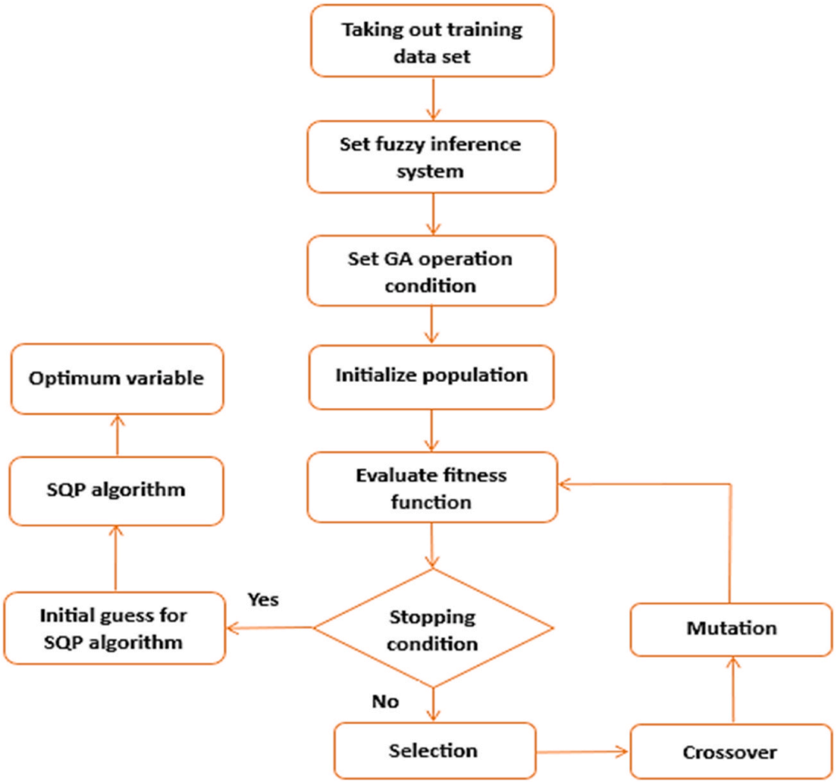

Fig. 9. Schematic representation of fuzzy and genetic hybrid algorithm procedure (Adapted and modified from Madaeni and Kurdian, [110]).

characteristics, namely flux and rejection, under various situations. These experimental results were then compared with the theoretically derived values of flux and rejection using a fuzzy inference method. The genetic algorithm, a very effective and methodical approach, was utilized to create a fuzzy model, as depicted in Fig. 9, to optimize the poorly comprehended, irregular, and intricate membership function, resulting in enhanced performance. A hybrid genetic algorithm was employed to optimize the parameters associated with the Gaussian membership functions in the premise and, subsequently, for each rule. The findings demonstrated that the fuzzy inference system (FIS) accurately forecasted the crucial parameters, flow, and rejection under various operational circumstances, with a tolerable margin of error. To put it otherwise, FIS can be utilized for modelling the microfiltration membrane, a procedure that is mathematically complex or, in numerous instances, unpredictable. AI-driven models in membrane processes for water and wastewater treatment offer numerous prospects for improving environmental systems in the future [110]. However, the specific needs and nature of the problem will determine the suitable approach to be selected by users.

Extensive research has been conducted on Artificial Neural Networks (ANN) due to their capacity to acquire knowledge about intricate procedures and generate comprehensive approximations of data [118]. Nevertheless, there is currently no available information regarding a study conducted on pilot-scale filtration systems and real-world monitoring data. The benefit of utilizing modelling techniques that rely on direct analysis of experimental data, such as fuzzy modelling, is that the outcomes are solely dependent on the data that is accessible. All influential parameters impact the collected data and are not necessary for modelling. Therefore, by gathering ample empirical data, fuzzy systems have the capability to approximate the system with any desired level of error. Therefore, modelling techniques that rely on the direct examination of actual data seem to be a highly favourable substitute for models that are based on speculative assumptions. A fuzzy system is primarily designed to establish a collection of localized input-output correlations that accurately depict a given process [110,123]. The process of system modelling consists of two primary stages: identifying the structure and optimizing the parameters. Structure identification involves the task of establishing the division of the input-output space and the required number of rules for the fuzzy system. Parameter optimization is a process that determines the best possible value for all parameters used in the fuzzy system [110]. Nevertheless, global experience has demonstrated that ensuring optimal circumstances is intricate, resulting in significant fluctuations in the effectiveness of pathogen eradication. Hence, AI–based optimization of membrane process conditions via filtration is discussed below.

4.2. Artificial intelligence (AI) tools for optimizing the membrane process during the removal of pathogens

There is a lack of comprehensive literature reporting on the use of artificial intelligence (AI) approaches in the exploration of membrane processes performance for water and wastewater treatment within the context of Industrial Revolution 4.0 (4IR) (especially in terms of water flux and membrane fouling) [31,32]. Therefore, AI tools for the optimization of membrane processes during biologics treatment are discussed next.

Artificial neural networks (ANN), as a data-driven technique, use a learning algorithm to establish relationships between variables (input and outputs) [116]. Focus has recently shifted to artificial intelligence-based modelling techniques such as ANN because of their preciseness and ability to effectively predict the efficiency of membrane-based processes. Their applications in environmental engineering and other fields of study are also promising [117].

To guarantee high-quality treated water, the operating conditions for membrane filtration cannot be precisely adjusted using the traditional optimization methods. Consequently, in the management of wastewater treatment, numerical techniques like artificial intelligence (AI) will help anticipate the requisite variables that are otherwise challenging to discover experimentally [124]. Artificial Intelligence (AI) is the ability of a computer or a computer-controlled device to perform sophisticated mental functions, including inference, reasoning, generalization, and experience-based learning [125]. In many contaminated locations, using artificial

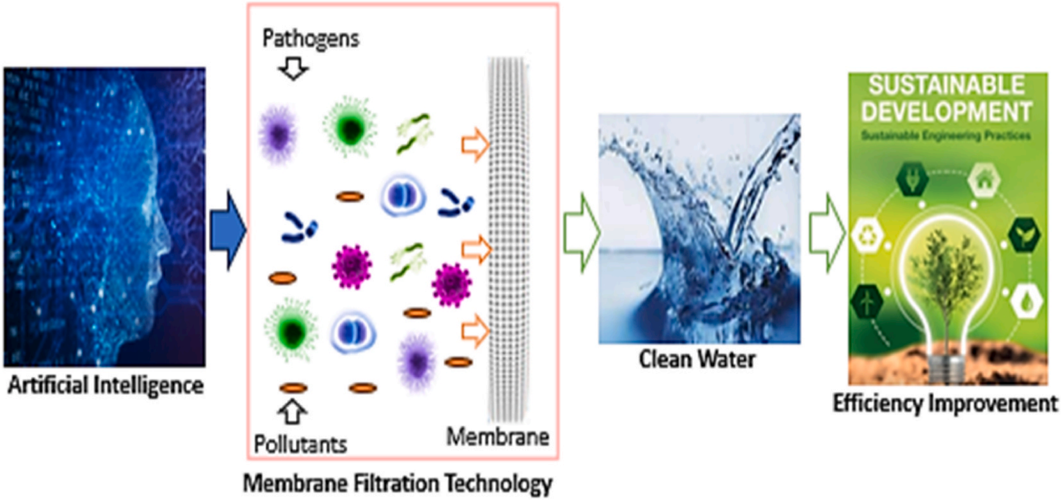

Fig. 10. Artificial intelligence tool using membrane process for wastewater treatment [124].

intelligence (AI) to regulate water quality has proven beneficial in supplying clean water supplies [126]. Machine learning and deep learning are the two primary methods for integrating artificial intelligence (AI) tools into wastewater treatment systems. The effectiveness of wastewater treatment and the quality of the treated wastewater are determined by several parameters and environmental conditions that complicate the wastewater treatment process [114].

Using computational fluid dynamics (CFD) to optimize membrane processes is costly and time-consuming. Thus, the integration of CFD with artificial intelligence (AI) can yield a viable hybrid model that can precisely forecast model outcomes and suitably enhance membrane operations and phase separation. Scientists are integrating AI into the wastewater treatment process to address these intricate issues. Artificial intelligence has been extensively applied in predicting and monitoring water quality, processing optimization, and managing and operating wastewater treatment facilities [116]. Several review papers on the use of AI in wastewater treatment have been published in recent years. Bhagat et al. for instance, reviewed the current state of AI and its promise for the future in simulating the removal of heavy metals from wastewater [127]. Similarly, Niu et al. described in detail how several AI techniques are used for membrane fouling [32]. Nevertheless, these studies have mainly concentrated on specific applications or algorithms rather than artificial intelligence (AI) tools for optimizing the membrane process during the removal of biologics, as shown in Fig. 10. Notably, AI is a potent instrument for delving into intricate wastewater treatment systems and enhancing the purity of water resources [114].

Some advantages of the ANN modelling approach include its ability to model complex non-linear problems, robustness, straightforwardness, water quality prediction, and demonstration of the contaminant transformation process. ANN could also be a helpful approach to identifying imminent risks [31,105,116]. An efficient and potent technique that can replicate these non-linear processes even in the face of changing environmental variables is the artificial neural network (ANN) [128,129]. Furthermore, compared to mathematical models based on regression, the ANN model produces more reliable and accurate findings when used for process optimization [130]. An artificial neural network (ANN) mimics the biological nervous systems of humans by operating several neurons or nodes concurrently in a parallel processing framework, as shown in Fig. 11. Artificial neural networks (ANNs) have been termed "black box" models since they can mimic any process with minimal background knowledge, which is another characteristic of AI tools [105]. The ability of this artificial neural network model to adapt and learn on its own allows it to show how each independent input affects a dependent response (output) [128].

According to the study conducted by Madaeni et al. [132], Fig. 12 displays the comparison between the data obtained from experimental results and the data predicted by the Artificial Neural Network (ANN) for both the training and validation sets. The variables being compared are flux and rejection. The figure demonstrates a satisfactory concurrence between the experimental and model data. To assess the resilience of the constructed Artificial Neural Network (ANN) model, around 15 % of the entire dataset was used for testing the model's predictability. Fig. 13 depicts a contrast between the experimental findings and the model's forecast for flux and rejection. There is a strong correlation between the predictions made by the model and the actual measurements of flow and rejection in the test data set.

Although, ANNs have proven useful in removing biologics, the efficiency, reliability, and scalability of membrane-based bioprocessing systems can be further improved by incorporating additional optimization and modelling techniques such as CFD, GA, RSM, hybrid modelling approaches, and machine learning ensemble techniques. By capitalizing on the synergistic advantages of these approaches, scholars have the potential to propel the current frontiers in biologics treatment and make valuable contributions to the advancement of water purification technologies that are both sustainable and efficient.

Several authors have developed various optimization strategies related to membrane-based technologies for removing biologics from wastewater, as summarized in Table 4.

The subsequent part provides a more in-depth analysis of the efficacy and constraints associated with the modelling and optimization of pathogen elimination using membrane-based methods.

5. Limitation and prospects of modelling and optimization of membrane-based removal of biologics from wastewater

AI-based models still have inherent limits that must be considered to enhance their performance in the future. AI models lack the capability to elucidate the interconnected relationships among physical characteristics, potentially constraining their ability to accurately accommodate modifications in building components or systems [114]. Furthermore, the process of creating AI models usually necessitates a substantial dataset to effectively train and evaluate a model with satisfactory precision. The development

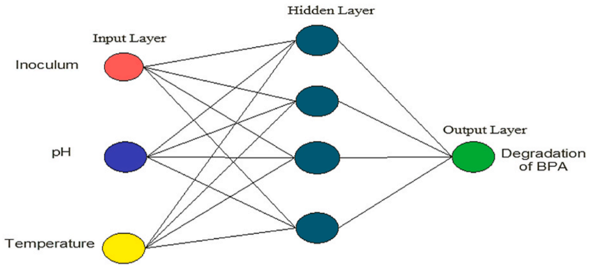

Fig. 11. Artificial Neural Network (ANN) structure for degradation of bisphenol A (BPA) (Adapted and modified from Fu et al. [131]).

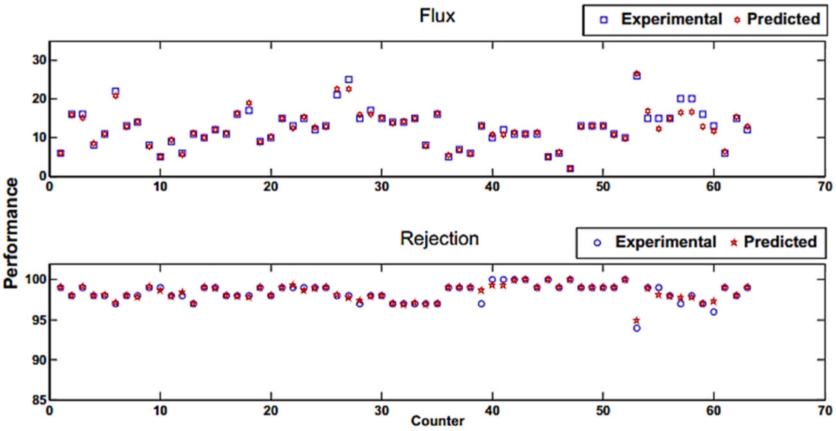

Fig. 12. Experimental flux and rejection and predicted by ANN for train and validation data. Reprinted with permission from Madaeni et al. [132].

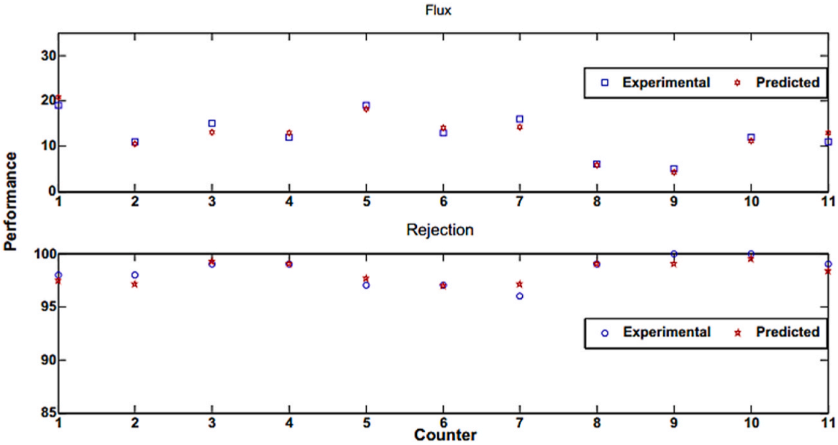

Fig. 13. Experimental flux and rejection and predicted by ANN for test data. Reprinted with permission from Madaeni et al. [132].

Table 4
Optimization strategies for membrane-based technologies for the removal of biologics in wastewater.

Membrane process	Wastewater type	Modelling approach	Parameter optimized	Reference
Rotating biological contactor with external membrane filtration	Synthetic wastewater	RSM	hydraulic retention time (HRT), and sludge retention time (SRT)	[133]
Microfiltration	Synthetic	Fussy logic	Flux and rejection	[110]
Photocatalytic membrane reactor: Microfiltration		RSM	hydraulic retention time (HRT), photocatalyst loading (PL), Initial virus loading	[134]
Ultrafiltration	Raw portable water	RSM	Polyaluminium chloride dose, flocculation retention time	[135]
Microfiltration, ultrafiltration, and reverse osmosis	Raw water	ANN		[117]
Microfiltration	Textile wastewater	RSM: Box–Behnken design		[136]
Any membrane process	Any wastewater type	Superstructure based optimization	Pore size, Operating pressure, Minimum particle size removed, Membrane materials, Membrane configuration	[137]

procedure must be carried out by highly skilled scientists who possess extensive expertise in both environmental aspects and data science technology. Despite these limitations, the merits of AI-based models continue to garner growing interest from researchers across. The instrument has been extensively utilized in recent years, and its specificities will be examined in the subsequent sections. AI-based models are expected to prioritize membrane fouling with the least care. Membrane fouling is a complex problem that is greatly influenced by many operational characteristics, making it challenging to simulate and predict accurately [32].

Researchers continue to face challenges in the modelling of membrane fouling. Over the past decade, there has been an equal amount of research conducted on the removal efficiencies of organic matter and nutrients, specifically nitrogen and phosphorus. On average, at least one report per year has been published, contributing to the global understanding of the potential of using AI models to simulate the performance of membrane filtration systems [119]. The AI tools exhibited a limited range of values with a high R^2 coefficient, ranging from 0.98 to almost 1.00, and an average value of 0.99. Simultaneously, traditional models exhibit a wide range of values for these parameters, ranging from 0.92 to 0.98, with an average value exceeding 0.96. The findings suggest that AI tools offer greater advantages compared to traditional mathematical models in terms of the streamlined model-building process and performance (as demonstrated in Section 4.1), as well as the high accuracy of the projected outcomes. Furthermore, the models possess the capability to accurately replicate not only the water flow but also the effectiveness of removing impurities, the occurrence of membrane fouling, and even the production of membranes for all types of membrane processes, encompassing pressure-driven, concentration-driven, and electrically driven systems. These tasks are typically challenging for traditional models to accomplish satisfactorily [75]. AI models offer a new approach to getting deeper insights into the complex phenomena observed in membrane water treatment processes, significantly enhancing the decision-making process in real-world systems. Consequently, the optimization and design of these membrane processes will become increasingly effortless and efficient in the next decades. The utilization of AI-based models in membrane processes for water and wastewater treatment offers numerous prospects for improving environmental systems in the future [28,124].

Furthermore, there will be a constant development of novel algorithms (i.e., new artificial intelligence tools) for membrane systems. As a result, the operational parameters and input sets utilized for modelling will be modified correspondingly. In the absence of updates to the current models, the accuracy of the model will diminish, resulting in inadequate simulation of the processes. The emergence of novel AI tools presents a promising approach to address these issues in the future, particularly through the advancement of hybrid AI models. While individual AI tools have shown satisfactory performance, hybrid AI technologies have proven the potential to enhance simulation performance [124]. The integration of artificial intelligence techniques with conventional mathematical models, as previously discussed. AI models are highly efficient in mimicking the performance of membrane systems. Nevertheless, there are instances when it is not appropriate, thereby necessitating a thorough comprehension of the underlying process mechanism. Simultaneously, mathematical models can expedite this process, but with diminished precision [32]. Hence, it is intriguing to explore the incorporation of artificial intelligence tools in fine-tuning specific parameters of traditional models to accurately depict processes in a more efficient simulation. The investigation of process parameters, membrane fouling, and the distinct generation of reversible and irreversible fouling has not yet been conducted [59]. AI models have high efficacy in forecasting fouling layers in this domain. They offer strategies to prevent fouling formation by regulating dynamic factors and minimizing overall operational expenses [138]. Among all these technologies, membrane-based wastewater treatment systems have shown a notable superiority in eliminating biologics from polluted water. Future investigations are likely to focus on the elimination of organic pollutants, emerging contaminants, and phosphorus. Moreover, the pursuit of multi-objective optimization and the examination of the dynamics of microbial communities are highly appealing areas of research.

AI-powered management solutions provide significant advantages in the field of water treatment. AI enhances membrane filtering operations by continuously analyzing real-time data from several sensors and sources. AI promotes efficiency, saves operational costs, and improves treatment outcomes by recognizing abnormalities and modifying parameters. In addition, predictive AI algorithms provide proactive maintenance scheduling, thereby prolonging the lifespan of membranes and reducing unforeseen periods of inactivity. The utilization of a data-driven strategy also enables the process of generating well-informed decisions by revealing concealed patterns and associations within sensor data. AI enables operators to immediately handle water quality issues and optimize treatment operations by offering practical insights. Furthermore, AI technologies like machine learning improve treatment procedures by analyzing past data and receiving immediate feedback, guaranteeing adherence to regulations, and increasing the effectiveness of pathogen elimination. The integration of the Internet of Things (IoT) and remote monitoring facilitates the capacity to manage and monitor systems in real-time from any location [139]. This integration enhances the dependability and resilience of systems by enabling timely reactions to emergencies.

To accelerate the advancement of water treatment management through the utilization of AI-driven membrane applications, it is imperative for organisations to adopt proactive strategies such as:

- The allocation of resources towards AI skills and knowledge facilitates internal innovation.
- Engaging in partnerships with AI technology providers grants access to customized solutions.
- Facilitating the exchange of data and fostering collaboration improves the precision of AI by utilizing shared datasets. Implementing regulatory measures guarantees the security and efficiency of AI-powered systems.
- Implementing pilot programs showcases advantages, hence promoting wider acceptance of AI in water treatment.

These processes jointly transform the treatment of pathogens, enhance efficiency, and guarantee universal access to safe water. The future scope of optimization and modelling of membrane technologies for removal of biologics is provided.

5.1. Future scope of optimization and modelling of membrane technology for removal of biologics from water

Within the field of bioprocessing, the optimization and modelling of membrane technology for the elimination of biologics are crucial areas that hold great promise. This emerging sector has the potential to completely transform the manufacture of biopharmaceuticals and the treatment of wastewater by providing improved efficiency, selectivity, and sustainability. Instead of being based solely on assumption, this assertion is supported by multiple solid arguments.

To begin with, the continuous advancement of material innovation is driving membrane technology towards unprecedented levels of effectiveness. Scientists are now investigating a wide range of materials, including nanocomposites and biomimetic membranes, which have the potential to exhibit exceptional performance properties. By utilizing these innovative materials, forthcoming membranes have the potential to exhibit unparalleled levels of selectivity and endurance, so paving the way for enhanced efficiency in the removal of biologics. Furthermore, the implementation of sophisticated membrane design methodologies is significantly transforming the field of separation science. These design advances, ranging from hierarchical structures to customised surface functionalities, provide the potential to reduce fouling and improve mass transfer qualities. These developments are not only abstract concepts; they embody concrete approaches to enhancing the efficiency of biologics removal operations at the molecular scale.

Concurrently, the emergence of multiscale modelling approaches is fundamentally transforming our comprehension of membrane functioning. Researchers are able to anticipate membrane function with exceptional accuracy thanks to the use of molecular dynamics simulations, machine learning techniques, and multiscale modelling methodologies. Through the utilization of computational modelling, researchers have the ability to optimize membrane characteristics and operational parameters in order to cater to particular applications involving the removal of biologics. This advancement marks the advent of personalised membrane systems. Moreover, the urgent need for sustainability is driving membrane technology towards more environmentally friendly options. Researchers are making efforts to reduce the environmental impact of membrane processes by using renewable materials, eco-friendly fabrication techniques, and energy-efficient operation strategies. The dedication to sustainability is not just a moral obligation but also a strategic requirement in a time characterised by increased environmental awareness. The future of membrane technology for the removal of biologics is contingent upon integration rather than isolation. The integration of membrane filtration with other separation techniques in hybrid processes is crucial for enhancing process intensification and achieving higher purifying yields. Through the limitations of certain fields of study and promoting cooperation, scientists can discover unexplored grounds in the improvement of efficiency and effectiveness in bioprocessing.

Lastly, the demand for the future potential of optimizing and modelling membrane technology for the removal of biologics is persuasive and complex. Researchers have the potential to transform biopharmaceutical production and wastewater treatment worldwide by combining material innovation, sophisticated design techniques, computational modelling, sustainability initiatives, and process integration. As we find ourselves at the threshold of a forthcoming era in the field of bioprocessing, the capacity for profound and revolutionary advancements is now unparalleled.

6. Conclusions

Various pathogenic microbes, including bacteria and viruses, have been detected in polluted water, causing a range of waterborne illnesses. Therefore, this study explored the application of membrane filtration (microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO)) in the removal of these pathogenic microbes. Membrane technology offers purer, cleaner, and pathogen-free water through the water separation method via a permeable membrane. With the development of membrane separation technologies, membranes are increasingly used as part of the conventional biological process and as an application alternative to conventional treatment. However, the limitations of conventional treatment units have necessitated the current review to evaluate advanced and hybrid wastewater treatment processes for removing pathogens from wastewater. The study gave a holistic evaluation of the significance of artificial intelligence (AI) tools in the mathematical modelling and optimization of the membrane-based process for removing pathogens from wastewater compared to the traditional modelling technique. The utilization of AI technology is anticipated to revolutionize the management and improvement of environmental systems, specifically membrane processes. By offering practical and valuable insights, AI may assist in the creation of advanced systems that are well-suited for future needs. In conclusion, the combination of membrane technologies and artificial intelligence tools will improve water quality, reduce cost, minimize waterborne disease, and enhance reused advanced-treated wastewater.

Data availability

No data was used for the research described in this article.

CRediT authorship contribution statement

Olawumi O. Sadare: Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Doris Oke:** Writing – review & editing. **Oluwagbenga A. Olawuni:** Writing – original draft, Methodology, Investigation. **Idris Azeez Olayiwola:** Writing – review & editing. **Kapil Moothi:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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