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The Recent Applications of Nanofiltration in Food Processing Industries

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ABSTRACT: Nanofiltration membranes are now commonly used because employing reverse osmosis membranes has resulted in excessive expenses. Since they can remove organic materials and soften water, nanofiltration may quickly destroy soluble particles, making them suitable for water with low total dissolved, such as surface water. They are essential for desalinating industrial areas and treating water and wastewater, as these areas include a wide range of ions and organic compounds that pose a significant risk to the environment. The world is facing insoluble water problems due to population increase, global warming, industrialization, and a global water crisis. Using NF is a realistic means to solve these issues and a practical way to get access to fresh, safe, and clean water. Food industries significantly contribute to the generation of microbial and chemical pollution in water sources. For instance, dairy wastewater is also suspected that a large amount of milk is wasted, producing an enormous amount of wastewater. Although the amount of protein is high, the protein in the water can be reused and improve water quality, and the treatment of wastewater can significantly reduce the cost and pollution of water, as a result, using NF for food industry effluent is attracting the growing amount of attention, and indeed, there is a large variety of nanofiltration constructions that can practically apply for water and wastewater treatment, along with different water quality such as acidic and alkaline environment. Following a meticulous analysis of nanofiltration (NF) technology and an extensive review of scholarly articles within this domain, the research demonstrated that pioneering advancements in nanotechnology, specifically NF, enhance water quality while mitigating both microbial and chemical contaminants.

Keywords: Desalination, Food Industries, Graphene-oxide, Nanofiltration, Thin-film Nanocomposite, Water and Wastewater Treatment.

Introduction

- *Background*

A considerable number of studies have discovered that despite water shortage, there has been a massive increase in water consumption and generating wastewater, according to these major issues, individuals, communities, and government are mindful of this crucial problem. Food industries have utilized a surprising amount of water, leading to the production of an enormous amount of wastewater, especially dairy industries. There is an insoluble problem limiting human society development, lack of fresh water and accessible energy (Ji *et al.*, 2017). Since

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water is an indispensable part of human life, water shortage, and environmental pollution are significant issues but according to an estimation by the World Water council, 3.9 billion people suffer from a lack of water by 2030 (Ji *et al*., 2017). Food industry wastewater treatment includes physical (sedimentation, filtration), chemical (coagulants, flocculants), biological (microorganisms), and advanced (membrane filtration, ozone) methods. Integrated management systems reducing water demand and wastewater generation are important, focusing on sustainable strategies. Treatment choice depends on the food process and effluent characteristics. Reusing processed water for non-potable purposes (e.g., irrigation, and industrial processes) promotes sustainable water management (Abdel-Fatah, 2023). Water and wastewater treatment include desalination, water softening, fluoride removal, and so on and Nanofiltration membranes play a pivotal role in a wide range variety of industrial applications like water and wastewater treatment and resource recovery. The rejection of NF membranes has a direct effect on energy costs and NF processes (Zhang *et al*., 2020). In recent years, nanofiltration (NF) has gained significant attention among various pressure-driven membrane processes like reverse osmosis, microfiltration, and ultrafiltration (Mallakpour and Azadi, 2022). The membranes have unique selectivity, making it a less energy-intensive, eco-friendly option, and enhanced final product quality. In recent years, the nanofiltration (NF) membrane process has gained significant attention for its ability to effectively separate inorganic salts and small organic molecules at lower pressures compared to reverse osmosis membrane processes (Lian *et al*., 2023). So, NF has become a standard unit operation in the food processing industry due to its reliability and economic attractiveness (Celik *et al*., 2023). NF is also used in wastewater treatment, recovery of value-added components from food waste, deacidification, and nutritional enrichments. They are commonly used in beverages, dairy, vegetable oils, and other food items for separation, concentration/purification, deacidification, demineralization, and microbial reduction. Considering the escalating challenges of water scarcity, environmental pollution from industrial wastewater, and the increasing demand for sustainable food processing techniques, this study aims to comprehensively assess the potential of NF technology in the food processing industry. By examining the application of NF membranes for treating wastewater, recovering valuable resources, and reducing the environmental impact of food production, this research seeks to provide valuable insights into the feasibility and effectiveness of NF as a sustainable solution for water management in the food sector. This includes evaluating the technology's performance in mitigating both microbial and chemical contamination, as well as its economic viability and operational considerations, ultimately contributing to a better understanding of how NF can be strategically implemented to address the growing need for efficient and environmentally responsible practices in the industry.

- *Challenges*

However, the main challenge in membrane science and technology is to develop low-cost, highly efficient, and long-lasting membranes. The trade-off relationship between permeance and selectivity, physical aging, and fouling are the main obstacles to developing effective membranes (Verma *et al*., 2024). The rising energy costs and the demand for products that offer better nutrition and less environmental impact have made membrane processing an appealing option for the food industry. NF is known for its efficient separation, reduction of wastewater, operation at low temperatures, fewer processing steps, and cost-effectiveness. The distinctive properties of NF, such as pore radius and surface charge density, play a significant role in separating various solutes (Mishra *et al*., 2023).

- ***Applications***

It has also found applications in pharmaceuticals due to rising energy costs, demand for high-quality products, and environmentally friendly processing methods. Meanwhile, in the pharmaceutical industry, NF technology plays a crucial role in removing drug contaminants and pharmaceutically active compounds from the environment (Mallakpour and Azadi, 2022). Semiconducting membranes combined with nanomaterials form a promising combination that could effectively remove various waste products from water, requiring minimal energy and reducing pollution (Li *et al*., 2023). According to the vital role of nanofiltration, selectively rejected ions and organic particles, it is utilized for seawater desalination application (Putri and Munasir, 2020). While there is a profound challenge to separate the solutes from organic solutions, it must be done in some industries. Organic solvent nanofiltration membranes are a modern field and in contrast to traditional nanofiltration, they always encounter a wide range of solvents, encompassing both polar and non-polar varieties (Vargas-Figueroa *et al*., 2023). OSNs are divided into two different classes, thin-film composite (TFC) and nanocomposite (TFN). These membranes are fabricated by similar layers, but TFN membranes made by a wide variety of nanoparticles led to porous and nanoporous membranes for improving the permeate flux (Dmitrenko *et al*., 2023). In addition, based on efficient selectivity, loose nanofiltration is a practical method to separate dyes and salts and efficient recovery and cyclic usage of valuable added components such as salts and dyes can be achieved by them (Kardel *et al*., 2023). Khoo *et al*. indicated the occurrence, risks, and type of emerging micropollutants (MPs) and elaborated on the rejection of emerging MPs by reverse osmosis and nanofiltration. It has been shown that thin-film nanofiltration and surface-modified thin-film composite membranes have noticeable rejection of MPs (Sardrood, 2023). A challenging and vital issue in successful water purification and resource recovery from unconventional water sources is the selective removal and enrichment of targeted particles, such as micropollutants, valuable materials, and mineral scalants (Kardel *et al*., 2023). Moreover, utilizing a crumpled polyamide layer to create piperazine (PIP)-based nanofiltration membranes is considered as instrumental method for reaching remarkable improvements in selectivity (Vargas-Figueroa *et al*., 2023).

- ***Recent Advances***

Pioneering membrane separation technology is the pragmatic approach to attaining perfect water treatment and producing high-quality freshwater. Graphene oxide is a state-of-the-art nanomaterial to keep the balance between membrane permeability and selectivity (Kardel *et al*., 2023). Graphene oxide (GO) is an adoptable next-generation membrane material due to its features. It has inimitable features such as ultrafast permeation and hydrophilicity, which led to its use as an acceptable nanomaterial in water purification. Despite all these features, its performance declines over time, owing to widening the pore size and it is a crucial problem (Verma *et al*., 2024). Additionally, graphene has a two-dimensional structure with exceptional features, therefore, it is possible to manufacture nanoporous ultrathin filtration membranes with these unique characteristics of graphene (Mishra *et al*., 2023). In recent years, there has been a huge increase in the need for reduction in organic solvent waste and OSN can be a new approach to solve this significant problem based on low energy costs in comparison with other usual techniques like adsorption, liquid-liquid extraction and solvent evaporation and membranes fabricated by 2D graphene-based materials brought about a revolution in this field. By simple method, these membranes provide high solvent flux and solute removal (Li *et al*., 2023). Additionally, their noticeable separation application led them to be the center of attention in a large variety of research, but stability is the underlying problem of these membranes in water purification. Indeed, a significant number of instrumental attempts have been dedicated to figure it out (Putri and Munasir, 2020). Owing to chemical stability and thermal resistance, a large amount of research has been conducted on graphene-based composite. Ag, Au, TiO_2, and Cu are some nanometals composed of graphene and its formative, produced graphene-based/nanometal membranes, having dramatic performance in water treatment and antibacterial properties (Vargas-Figueroa *et al*., 2023). Unfortunately, membrane fouling is a fundamental problem that considerably declines their efficient performance. There are a large number of materials like zwitterionic polymers, neutral polymers, polyelectrolytes, amphiphilic polymers, quaternary ammonium polymers, biopolymers, hydrophilic polymers, polydopamine, inorganic salts, and nanomaterials can be used to sort out this problem (Dmitrenko *et al*., 2023). Moreover, common nanofiltration membranes are based on TFC structure, including a thin rejection layer such as polyamide, a porous substrate layer, and a non-woven fabric support (Mallakpour and Azadi, 2022), (Ji *et al*., 2017). Designing and fabricating high-efficient nanofiltration membranes with substantial flexibility is achieved through TFC structure, allowing individual optimization rejection and support layers (Ji *et al*., 2017), (Lian *et al*., 2023). The top thin rejection layer has positive effects on particle rejection of nanofiltration membranes (Ji *et al*., 2017). Interfacial polymerization (IP) (Celik *et al*., 2023), surface coating/grafting (Verma *et al*., 2024), layer-by-layer deposition (Mishra *et al*., 2023), and so-gel process (Li *et al*., 2023) are some approaches that are taken to create the thin layer (Ji *et al*., 2017). There are some materials used for nanofiltration membrane preparation via IP: Polyamide used for NF and RO (Mallakpour and Azadi, 2022), Poly(bio-amide) used for NF membranes with high permeability (Putri and Munasir, 2020), Polyester used for NF membranes with improved chlorine stability (Vargas-Figueroa *et al*., 2023), Polyimide used for OSN (Dmitrenko *et al*., 2023), and Polyaniline used for OSN and electrically conductive membranes (Ji *et al*., 2017), (Lian *et al*., 2023), (Celik *et al*., 2023). On the other hand, there are other membranes utilizing different materials and structures such as Nano-zeolites for high-permeable nanocomposite thin-film, Aquaporin for aquaporin membranes, Carbon nanotubes for Anti-biofouling membranes, Nano-Ag for Anti-biofouling membranes, Nano-Tio2 for Nanocomposite membranes with high performance and thin film membranes that react to chemicals, and Nano-magnetite for Forward osmosis (Verma *et al*., 2024), (Mishra *et al*., 2023). Some Nanomaterial membranes with their applications are introduced: Aquaporin-based biomimetic membrane for low-pressure desalination (Li *et al*., 2023), Carbon nanotubes and membranes for Desalination and point-of-use, and highly biodegradable pollutants (pharmaceuticals, antibiotics) (Putri and Munasir, 2020), Magnetic NPs for advanced wastewater treatment and disinfection; remediation (Vargas-Figueroa *et al*., 2023), Nanocomposite membranes for Reverse osmosis, or the elimination of micropollutants (Dmitrenko *et al*., 2023), Nanofiber membranes for Water treatment, standalone filtration device, filter cartridge, ultrafiltration, and prefiltration (Kardel *et al*., 2023), Nanofiltration membranes for Reduction of color, heavy metals, hardness, and odor (Sardrood, 2023), (Nano)zeolites for Disinfection processes (Kardel *et al*., 2023), Self-assembling membranes for Ultrafiltration (Vargas-Figueroa *et al*., 2023), Nanoscale zerovalent iron particles for Treatment & remediation of wastewater (chlorinated hydrocarbon, perchlorates) (Dmitrenko *et al*., 2023), Ag and Tio_2 Nanoparticles for Antibiofouling surfaces, decontamination of organic compounds, remote regions, and point-of-use water disinfection (Kardel *et al*., 2023) and (Sardrood, 2023) and Polymeric nano adsorbents (dendrimers) for Elimination of heavy metals and organics (Mallakpour and Azadi, 2022), (Mishra *et al*., 2023). In this review, the graphene-oxide membrane is investigated, therefore, synthesis of graphene composite with their respective adsorbates are reported: Fe_3O_4@GO by Co-precipitation method with Cu(II) (Li *et al*., 2023), GO–carbon composite by Sol-gel method with Hg(II) (Putri and Munasir, 2020), GO–$ZrO(OH)_2$ by Hydrothermal co-precipitation method with As(III) & As(V) (Vargas-Figueroa *et al*., 2023), Polyamide-graphene by Interfacial polymerization with Sb(III) (Dmitrenko *et al*., 2023), RGO/silica composites by Sol-gel method with Oil (Kardel *et al*., 2023), GO/bentonite composite by Modified Hummers' method with Toluidine blue (Sardrood, 2023), Fe_3O_4@GO-thiourea by Solvothermal method with Coomassie brilliant blue (Kardel *et al*., 2023), GO-magnetic iron oxide nanoparticles by Sonochemical method with Methyl blue, GO-polystyrene by Polymerization with Reactive blue, Direct red and Acid blue, PDA-RGO-kaolin composites by Polymerization method with Methyl blue, CoFe2O_4/GO by Hydrothermal method with Methylene blue, Rhodamine B, GO-montmorillonite by Solvent method with Crystal violet, Hollow carbon spheres/graphene by Hydrothermal method with Methyl orange, Rhodamine B, Organic solvents, Graphene-carbon nanotube (GCNT) by Modified Hummers' method with Methyl blue, RGO/iron oxide composites by Co-precipitation with Naphthalene, 1-Naphthol, Graphene-metal organic framework composites by Crystallization with Benzene, Fe3O4 grafted GO by Co-precipitation with 2,4,4-Trichlo robiphenyl (PCB 28) and Graphene/MnO2 composite by In situ hydrothermal method with Tetracycline (Vargas-Figueroa *et al*., 2023). Most studies in this field have focused on chemical aspects of graphene-oxide synthesis but this review will take a closer look at green synthesis. Based on the study (Dmitrenko *et al*., 2023) that worked on relevant publications and patents of NF and used a bibliometric approach to analyze the research trends in nanofiltration membrane technology, which covered scientific papers from 1988 to 2011 and patent data from the same period, this comprehensive study was done. The above-mentioned study showed significant growth in publication outputs over the past 24 years. China has exhibited rapid growth in NFM papers and holds the most global NFM patents. The US focused on biochemistry and molecular biology, while China's NFM papers focused on energy and agriculture. China, the US, and Japan held a strong technological advantage in water treatment and separation technology. Nanofiltration technology has seen significant growth in research interest over the past decade and primary areas of interest in nanofiltration research include water processing, membrane fabrication, organic solvent nanofiltration, pharmaceutical and biological applications, design and economics of nanofiltration processes, and review articles (Kardel *et al*., 2023). By 2030, the bar chart undeniably demonstrates a substantial surge in the global annual nanofiltration market for the food industry, water, and wastewater (Figure 1).

This chart illustrates the growing interest in utilizing Nanofiltration for various applications, particularly in the food and beverage industries. This is due to increasing energy costs, elevated demand for high-nutrition food products, and the rising popularity of environmentally friendly processing methods. As a result, there is a pie chart showing the current scenario of published articles on NF membranes for food industries (Figure 2).

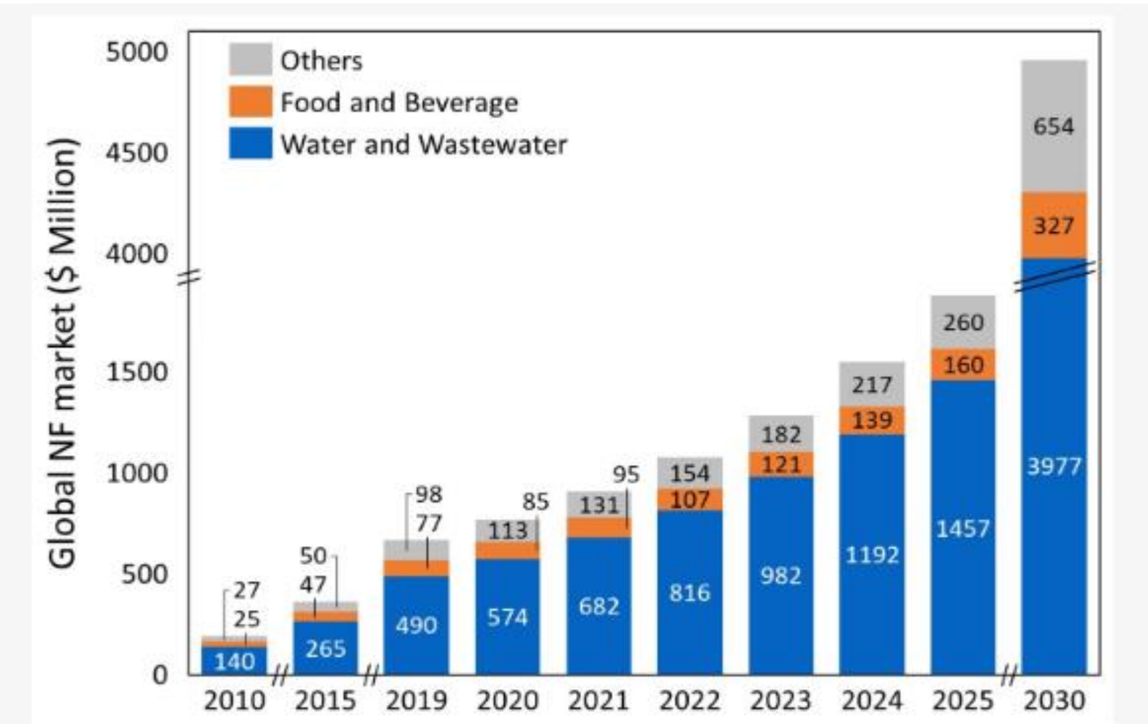

Fig. 1. Global annual NF market per application in $ million, including the projected growth for 2020-2030 [60].

The data clearly shows that plant extract is the dominant segment, owing to its use of bioactive compounds in various industries including functional food processing, pharmaceuticals, and green synthesis. The conventional techniques for the preparation of nanomaterials have been considered hazardous to the environment because toxic chemicals are used, the costs are very high, and further harmful by-products increase environmental degradation (Lian *et al*., 2023). In recent years, Green synthesis has been a commonly utilized method for producing nanomaterials, specifically nanocomposites. Nanotechnology encompasses the manipulation of materials at the nanoscale (1 to 100 nm) and presents diverse benefits within fields such as dentistry and pharmaceuticals. The integration of green chemistry is imperative for the development of safe and environmentally friendly nanomaterials, thereby ensuring widespread acceptance in the realm of nanotechnology. Furthermore, the utilization of plants and their extracts for the economical and efficient synthesis of nanoparticles provides a sustainable alternative for large-scale production (Celik *et al*., 2023). A bar chart shows a significant increase in the North America wastewater treatment market in food industries (Figure 3.). Over 300 million tons of organic waste are generated annually in the United States from agricultural and food processing industries, posing a global challenge (Verma *et al*., 2024).

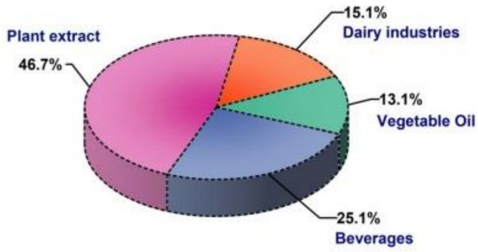

Fig. 2. Current scenario of published articles on NF membranes for food industries Verma *et al*

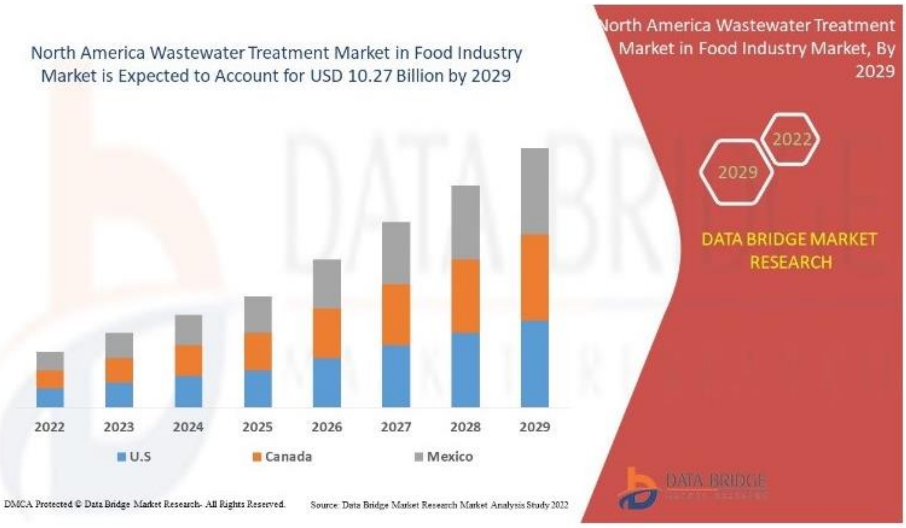

Fig. 3. North America Wastewater Treatment Market in Food Industry. Data source: (https://www.databridgemarketresearch.com/reports/northnorth america1.jpg-america-wastewater-treatment-market), date of data collection Nov 2022

Future advancements in wastewater treatment aim to minimize carbon emissions and maximize water reuse to ensure a sustainable future. Water scarcity in the food industry has led to the consideration of unconventional water resources like wastewater and rainwater. Membrane technology plays a crucial role in minimizing contaminants and enhancing treatment efficiency. It prevents industrial pollutants from entering the environment and aids in recycling food industry waste. Specific membranes are being developed to efficiently target and remove contaminants. This technology is essential for treating wastewater from industries like the food sector with minimal energy requirements [Verma *et al* 2019].

- ***Nanofiltration History***

Cadotte *et al*. in 1988 introduced new membranes as "quo; nanofiltration" quo; and stated that most attraction was drawn to reverse osmosis and its function in seawater usage. However, due to its high rejection, new membranes were able to produce less removal of salt or salt rejection from a feed stream (diafiltration). Operating at lower net driving pressure is important to all users. For this reason, three tailored membranes were reported: first of all, XP45 was a polyamide membrane with a low removal of NaCl, a candidate for salty cheese whey process and pharmaceutical preparations, secondly, NF70 was a low-pressure polyamide membrane and suitable for brackish water and organic-laden raw water and finally, XP20 was a novel membrane for preserving electroless copper plating baths (Kardel *et al*., 2023). Similarity, since 1985, Erik Roesink worked on new special membranes that were thermoresistant, steam sterilizable, and hydrophilic, additionally, performed well for food processing, hospitals, and wastewater purification (Sardrood, 2023). In a large variety of applications, using forward osmosis can be fruitful, like wastewater treatment, desalination, food industries, and dissolved metal rejection (Kardel *et al*., 2023). The wastewater of the food industry is a significant issue because it plays a vital role in human life. Additionally, they utilize a significant amount of water in production processes, leading to an astonishing amount of water pollution, and causing negative effects on the environmental safety and economy (Sardrood, 2023). The percentage of total water in the food industry used by different sectors is shown in Figure 4.

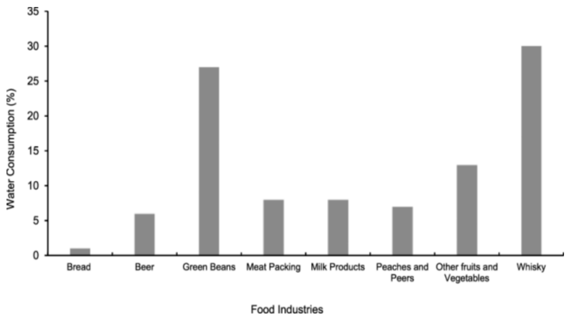

Fig. 4. Percentage of total water in the food industry used by different sectors [67].

A high pollutant wastewater of food industries includes carbohydrates, proteins, blood, inorganic and organic salts, grease, oil, and leavenings (Kardel *et al*., 2023). The contamination sources contain plant and animal debris, dissolved and suspended substances, or other pollutants such as fats, ferments, micro-organisms, or micro-pollutants. They include microplastics, hormones, antibiotics, pesticides, and various chemicals, affected rivers, aquifers, human health, and the biodiversity of nearby aquatic and terrestrial ecosystems. Hence there is a need to take prevention and treatment measures to reduce pollution before discharge into the environment because the value of some pollutant materials such as nitrate and phosphate are generally above the limited standards determined by WHO. It is suggested that food and drinking wastewater are dangerous to flow into natural ecosystems before treatment (Sardrood, 2023). (Kardel *et al.*, 2023) (Sardrood, 2023) Furthermore, the food and beverage industries generate approximately 80 million m3 of wastewater a day and in the U.S. the food and drinking processing and manufacturing facilities produce around 14,000 million gallons a day, moreover, due to populous countries such as China, India, and Japan, generating food industry wastewater is a challenging issue in Asia. Population growth, urbanization, changing dietary habits, and industrialization are the most important factors in growing wastewater generation from food industries. The meat industry produces a high amount of wastewater due to the handling activities involved in the industry, such as cleaning, sanitizing, and product processing of meats, to keep up with the standards of hygiene. The wastewater usually carries high organic load, nutrient content, and pathogen contamination. Additionally, the seafood processing industry is challenging because of organic load, nutrient pollution, odor, aesthetics, and pathogens. Similarly, the dairy industry is a crucial issue based on the same reason and involves some activities like milk pasteurization, butter manufacturing, and cheese processing. Processed milk amount, product and equipment types, processing method, system management, and washing mechanism determine the effluent and importantly it is non-biodegradable and includes organic compounds (Lian *et al.*, 2023), (Celik *et al.*, 2023). Surprisingly, 931 million tons of food were wasted in 2019, and it was around 17% off all available food in stores. Apart from low concentrations of heavy metals and toxicants, food processing wastewater includes valuable materials with significant concentrations such as proteins and lipids (Abdel-Fatah, 2023) As utilizing membranes helps to separate molecules and micro-organisms, needs moderate energy consumption, and minimizes thermal damage (Verma *et al.*, 2024), this state-of-the-art technology can be used in food processing applications. Membranes mainly apply in the beverage and dairy industries. Using cross-flow microfiltration results in removing bacteria and milk globular fat fractionation for producing drinking milk and cheese milk (Mishra *et al.*, 2023). On the other hand, increasing drinking water shortage and reusing water and wastewater play a pivotal role in economic and ecological issues (Sardrood, 2023) but it is mostly dependent on new acceptable technology for water and wastewater treatment It is a challenging issue owing to a large variety of industrial effluent, although, it can be achieved along with significant progress in efficiency and cost-effectiveness of membrane technology (Lian *et al.*, 2023). Physical and chemical treatment methods can be combined with biological methods to reach high-quality water by effective rejection. These methods include membrane technology such as NF and RO, gravitational methods, and adsorption (Kardel *et al.*, 2023). Table 1 lists various applications of nanofiltration (NF) across different sectors of the food industry.

Dairy processing industries contribute to a substantial volume of wastewater as a byproduct of various essential operations, including heating, cooling, disinfection, cleaning, and washing. It is estimated that approximately 10 liters of wastewater are generated per liter of milk processed. The effluent from the dairy industry comprises a high concentration of organic and

Table 1. Potential applications of nanofiltration in the food industry and environmental protection (Mallakpour and Azadi, 2022)

Industry	Application
Dairy industry	- Partial demineralization of whey - Concentration of lactose in whey ultrafiltration permeate - Cleaning in Place (CIP) wastewater treatment
Fruits and Vegetables	- Fruit juice concentration - Pigment (antocyanins) concentration - Aroma concentration from condensate of the evaporation process for fruit juice concentrate production - Waste water treatment
Sugar industry	- Preconcentration of the clarified sugar beet - extract solution - Process and washing water recycling - Molasse purification for reuse
Grain Products	- Recovery of soy whey proteins - Oil de-gumming and refining - Com refining steep water concentration - Waste water treatment
Biotechnology	- Production of high quality water - Downstream processing: product removal, desalting, concentration - Waste water treatment
Pharmaceutical Industry	- Product removal and concentration - Product purification, desalting - Waste water treatment - Organic solvent recycling
Metal working Industry	- Cutting - oil (microemulsion) treatment - Metal ion recovery from wastewater of plating industry
Chemical Industry	- Reaction product removal, concentration - CIP wastewater treatment and recycling - Waste water treatment
Drinking and Process Water	- Removal of Total Organic Carbon (TOC), Dissolved Organic Carbon (DOC), Total Inorganic and Organic Matter Filtration Performance (TIIMFP) - Removal of heavy metals and arsenic - Water softening - Recycle and reuse of process water

inorganic pollutants, including lactose, mineral salts, detergents, lipids, milk fats, carbohydrates, soluble proteins, and certain heavy metals. The majority of wastewater in the dairy industry comes from cheese processing. The elevated presence of pollutants in dairy wastewater has a profound impact on the environment and ecological systems. This results in escalated concentrations of Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD5), Total Nitrogen (TN), Ammonium Nitrogen (NH4-N), and Total Phosphorus (TP) in wastewater, which has the potential to disrupt aquatic systems. The global surge in milk production over the past two decades has exacerbated the issue, leading to a substantial daily generation of wastewater. It is imperative to prioritize the appropriate treatment and disposal of this wastewater to avert environmental contamination and mitigate ecological harm (Li *et al*., 2023). Hence, the implementation of cutting-edge technologies such as nanotechnology and nanofiltration holds promise in mitigating environmental wastewater and effluent, addressing global warming through a reduction in greenhouse gas emissions, and promoting energy efficiency.

- *Literature Review*

Vatai studied Nanofiltration applications in food technology and environmental protection. The study focused on investigating the influence of process parameters on permeate flux and sugar/total solid rejection in a three-step membrane process involving reverse osmosis (RO) and nanofiltration (NF) steps. The application possibilities of nanofiltration were found to be very promising, with an expectation of intensive development in NF application in the coming years (Mallakpour and Azadi, 2022). Wang *et al*. have demonstrated that the diafiltration process using NF membrane is a viable method for concentrating oligosaccharides (OS) while simultaneously removing NaCl from soybean whey wastewater (Lian *et al*., 2023). Nguyen *et al*. stated that Cottage cheese whey, a problematic waste due to its low concentration, high salt content, and acidity, can be improved through nanofiltration to increase solids content fourfold, remove most salts and acid, and create a stable product suitable for use in dairy and other food products. (Celik *et al*., 2023). Almanasrah *et al*. discussed that Carob kibbles contain valuable phenolic compounds and sugars. This study aims to produce two natural extracts: one high in catechin for the nutraceuticals market, and another rich in sugars for the food industry. The process involves membrane technology and aims to minimize waste. Different extraction methods were considered, and an integrated scheme for producing fractionated extracts was proposed based on experimental work (Verma *et al*., 2024). Mohammad *et al*. discussed that membrane performance has been effectively enhanced by using nanomaterials in the thin film. Nanofiltration has succeeded in different fields such as water and wastewater treatment and food industries with a large variety of selectivity (Mishra *et al*., 2023). Chandrapala *et al*. highlighted that the dairy industry faces challenges in using acid whey due to its high lactate concentrations. They used raw acid whey after microfiltration, as well as laboratory-prepared solutions of lactic acid and lactose, and sodium lactate and lactose for comparison. The study found that the removal of lactic acid increased with the degree of acid dissociation, with around 50% of the lactate being removed at pH ~3 due to lower dissociation. Additionally, over 90% of the lactose was retained at all pH levels tested. Interestingly, the molecular weight cutoff and permeability of the membranes had minimal impact on the separation performance (Li *et al*., 2023). Chandrapala *et al*. emphasized that the dairy industry struggles with processing acid whey due to the difficulty of crystallizing lactose in the presence of lactic acid and suggested that nanofiltration could be useful in making the most of this industrial by-product (Putri and Munasir, 2020). Macedo *et al*. worked on Nanofiltration Membranes for Agro-Industrial Effluents Purification and focused on the purification of agro-industrial effluents, specifically from dairy, olive mill, tomato, and artichoke wastewater using nanofiltration technology. Tomato and artichoke wastewater were treated using a combination of biological treatment and nanofiltration (NF) to improve productivity and extend the membrane lifespan. Olive mill wastewater disposal challenges were highlighted, stressing the need for NF due to high organic load and phenolic compounds, essential for purifying and recovering valuable compounds. Nanofiltration is crucial for separating and valorizing whey components in dairy wastewaters, focusing on protein and lactose recovery while addressing fouling challenges and enhancing process efficiency. Circular economic principles were emphasized in agro-industrial effluent treatment, emphasizing the recovery of valuable molecules and water for process sustainability. The potential growth of nanofiltration in Mediterranean countries facing water scarcity was discussed as a promising solution for effluent purification (Vargas-Figueroa *et al*., 2023). Ghalamara *et al*. researched producing bioactive protein/peptide fractions from sardine cooking effluent. The purpose of this work was to develop a pilot-scale integrated membrane process to obtain high protein/peptide fractions with low NaCl content and optimized bioactive properties from sardine cooking effluents. The process involved ultrafiltration (UF) and nanofiltration (NF) followed by reverse osmosis (RO). The research showed that the fractions obtained had potential applications in the food, pharmaceutical, or cosmetic industries due to their bioactive properties (Dmitrenko *et al*., 2023). Li *et al*. focused on the use of nanofiltration (NF) technology for separating and purifying saccharides from biomass. NF has shown promise as a technology for saccharide extraction due to its low energy consumption, minimal environmental impact, and ability to preserve the inherent properties of the product during separation (Kardel *et al*., 2023). An *et al*. put forward that the membranes which are based on graphene oxide, are economical and reasonable and can be more renitent to organic solvents and oxidants, have more hydrophilicity, and less membrane blockage. Since their separation operation is better, it is possible to use them in industrial wastewater treatment (Sardrood, 2023). Lee *et al*. elaborated on industrial activities that produce acidic wastewater and deeply analyzed the performance of commercial nanofiltration membranes, especially under low solution pH conditions. Eventually, it was explained a large range of technical approaches to manufacturing acid-resistant nanofiltration membranes through emphasizing the vital mechanism to improve acid stability (Kardel *et al*., 2023). Innovative biological systems, combined with filtration, disinfection, and membranes, can elevate recovery rates by up to 90%, surpassing individual primary (<10%) or biological methods (≤50%). Advanced treatment methods can achieve up to 95% water recovery, exceeding UN goals for clean water and sanitation (Goal 6). This progress aligns with climate action objectives and safeguards vital water-rich habitats (Goal 13) (Sardrood, 2023). Voicu and Thakur specially discussed removing salts, heavy metals, and lower molecular weight organic compounds. Furthermore, they offered modern methods for synthesizing to attain thin-film composite nanofiltration membranes (Kardel *et al*., 2023). Guo *et al*. in 2022, emphasized fit-for-purpose design, resulting in improving high percentage separation of other suspended particles besides salt (Ji *et al*., 2017). Feng *et al*. worked on loose nanofiltration membranes and chiefly stated the latest progress in manufacturing high-efficient membranes for separating dye and salt-like phase inversion (Kardel *et al*., 2023). Joshi and Gururani stated that pollution based on dye and heavy metals can be eradicated more than 90% by a surprising number of graphene or reduced graphene oxide-based nanocomposites (Sardrood, 2023). Hossein *et al*. reported recent advances in utilizing graphene-based absorbents for eradicating a large variety of organic and inorganic suspended particles in wastewater and due to different experimental conditions, a critical review was prepared on synthesizing graphene, systematic absorption, and desorption mechanisms besides their polluter elimination performances (Sardrood, 2023). Abdel-Fatah conducted a review and the chief usage of NF technology in water recycling, wastewater treatment, water softening, and removing salt was presented (Abdel-Fatah, 2023). Pezeshki *et al*. reviewed arsenic rejection by NF and RO and presented that membrane processes offer effective contaminant removal with benefits like no need for chemicals, no sludge production, and removal up to WHO standards. Despite the risk of membrane clogging, pre-treatment can mitigate this issue, making membrane processes a preferred method for contaminant removal (Lian *et al*., 2023). Divyadeepika *et al*. stated that too little and too many F- ions are both harmful and the amount of F- ions was increased by volcanic ash and many fertilizers. There are some chief technologies for F-rejection such as green nanomaterials and membrane technology and zeolites, alumina, organic-based carbon-based nanotubes, and graphite are used for wastewater treatment (Celik *et al*., 2023). Amjad-iranagh and Mahimani discussed that polymer nanocomposite membranes have been commonly used to refine impure and contaminated water and wastewater but applying them is associated with some crucial problems such as blockage resulting in generating new membrane generations without those problems. Combining nanofillers like carbon nanotubes, graphene oxide and titanium dioxide, with these membranes has led to outstanding abilities and there has been a dramatic decline in problems (Verma *et al*., 2024). Dehghani *et al*. presented that there has been a substantial increase in the utilization of pesticides. After evaluating a wide range of pioneering technologies like advanced oxidation process, membrane filtration, and absorbent types (carbon nanotubes, carbon nanofiber, carbon aerogel, graphene oxide, and other types), used for declining toxic pesticides from water and wastewater, it was shown that it is possible to decompose and eradicate pesticides by nanocomposites (Mishra *et al*., 2023). Guo *et al*. introduced a novel NF membrane, having an active layer including hydrophilic carbon-carbon covalent, highly caused ion rejections and antifouling of protein and bacteria in NF membranes. Under their features, they could be the perfect choice for environments including high pollution with acidic or alkaline conditions (Li *et al*., 2023). Liu *et al*. described that developing a facile modification strategy improved the rejection of salt/organics by using sulfonic acid group features such as high hydrophilicity. Generated membrane had shown more than doubled water permeability and substantially declined the removal of Ca2+ and Mg2+ but kept a high rejection of organic micropollutants, additionally, it excellently performed in selective removal between mineral salts and natural organic matter, compared to a wide range of commercial nanofiltration membranes (Putri and Munasir, 2020). External literature reviews of Nanofiltration are shown in Table 2.

Table 2. Synthesis Methods and Adsorbates of Graphene Composite Membranes

No.	**references**	**Title of Project**	**Filtration types**	**Filter application**	**Results**
1	(Liu *et al.*, 2021)	A Facile and Scalable Method of Fabrication of Large-Area Ultrathin Graphene Oxide Nanofiltration Membrane	scalable ultrathin uniform GO membrane	Rejection of Na2SO4	The fabricated membrane showed superior water permeability of over 60.0 kg m−2 h−1 and a high separation efficiency of over 96.0% for a sodium sulfate (Na_2SO_4) solution
2	(Zhang *et al.*, 2022)	General synthesis of ultrafine metal oxide/reduced graphene oxide nanocomposites for ultrahigh-flux nanofiltration membrane	the rGO membranes (ultrahigh-flux nanofiltration membrane)	Dye rejection	By functioning as pillars, the nanoparticles remarkably increase both vertical interlayer spacing and lateral tortuous paths of the rGO membranes and selectivity up to 98% in the size-exclusion separation of methyl blue.
3	(Guo *et al.*, 2024)	Hydrophilic carbon-carbon covalent linkage network structure for strong acid/alkali resistant and antifouling nanofiltration membrane	a new nanofiltration membrane with an active layer composed of hydrophilic carbon-carbon covalent bond linkage network	ion rejection in highly acidic or alkaline environments	The carbon-carbon covalent bond (C–C) chemistry used in the preparation of the NF membrane results in exceptional durability towards acid and base, enabling it to maintain its ion separation efficiency under strong acidic and alkaline conditions. Additionally, the water-attracting nature of polyDMAPS and PAA effectively prevents the fouling of protein and bacteria on the NF membrane surface.
4	(Zheng *et al.*, 2021)	Highly stable graphene oxide composite nanofiltration membrane	GO hybrid lamellar membranes	dye desalination, rejection of salt solution	The optimal composite membrane delivers a pure water-flux up to 26.0 L m−2 h−1 bar with a 99.9% rejection of methylene blue and eosin under an ultra-low pressure nanofiltration condition.
5	(Cui *et al.*, 2024)	C_3N_4-interlayer-mediated interfacial polymerization of homopolymer nanofiltration membranes for efficient water purification	Interlayered thin film composite (TFNi) membranes	Na_2SO_4 rejection	The best TFNi membrane exhibits high water, nearly twice as high as that of the membrane without g-C3N4 interlayer, while maintaining a comparable Na_2SO_4 rejection efficiency.
6	(Lin *et al.*, 2024)	Catalytic pre-coat on ceramic nanofiltration membranes for	Ceramic nanofiltration (NF)	natural organic matter (NOM)/ Real water	The catalyst pre-coat layer with a pore size of 0.1–0.5 μm was able to segregate the large-sized colloids

No.	references	Title of Project	Filtration types	Filter application	Results
		segregation and Fenton cleaning of high-resistance colloids in direct surface water treatment			from the TiO2 separation layer during direct filtration of the raw water. In the meantime, the TiO2 separation layer of the membrane exerted a high NOM rejection of approximately 90%, measured as dissolved organic carbon.
7	(Wang *et al.*, 2019)	Accessing of graphene oxide (GO) nanofiltration membranes for microbial and fouling resistance	GO membranes	Rejection of Na2SO4, NaCl, Mg2SO4 and MgCl2	The antimicrobial test demonstrated that GO nanosheets lose their antimicrobial activity after they are stacked together.
8	(Salehpour *et al.*, 2024)	Arsenic removal from aqueous solution using PWN-type zeolite membrane: A theoretical investigation	PWN-type zeolite membranes	Rejection of dissolved arsenic ions	The zeolite's nanoporous structure immobilizes arsenic ions while permitting water transport.
9	(Lenaerts *et al.*, 2024)	Development of tuneable polyamine top layer for nanofiltration with high stability in bleach and at extreme pHs	thin film composite membranes, comprising a thin top layer on top of a porous support	bleach and pH <1, >13/Rose Bengal rejection	resulting in a membrane with both very good separation performance (e.g. 99.6 % Rose Bengal rejection) and excellent stability in extreme conditions
10	(Alonso *et al.*, 2024)	Evaluation of nanofiltration and reverse osmosis membranes for efficient rejection of organic micropollutants	The selection included membranes with diverse performances in terms of water permeance and salt/solute rejection, i.e., from “tight” high sodium chloride rejecting fully aromatic polyamide membranes	standard brackish water	The best performing TFC membranes — a lab-made semi-aromatic piperazine-based NF polyamide membrane and a fully aromatic commercial polyamide NF membrane (NF1) — displayed excellent rejection of OMPs comparable to a commercial RO seawater membrane (RO4), but exhibited ~2-fold and ~6-fold higher water permeance, respectively.
11	(Scheepers *et al.*, 2024)	Nanofiltration membrane performance of layer-by-layer membranes with different polyelectrolyte concentrations	polyelectrolytes, PDADMAC, and PSS	0.05 M salt solution	The higher salt concentration resulted in more abundant PDADMAC in the membrane.
12	(Kandjou *et*	Systematic	Crosslinked graphene oxide	a lab-scale	performance improvement

No.	references	Title of Project	Filtration types	Filter application	Results
	al., 2023)	covalent crosslinking of graphene oxide membranes using 1,3,5 triazine 2,4,6 triamine for enhanced structural intactness and improved nanofiltration performance	nanofiltration membranes	nanofiltration device was constructed for flux and rejection analysis	with covalent crosslinking was imminent as an up to a 100% rejection of methylene blue
13	(Li *et al*., 2023)	Nanofiltration Membranes with Salt-Responsive Ion Valves for Enhanced Separation Performance in Brackish Water Treatment: A Battle against the Limitation of Salt Concentration	a nanofiltration membrane with the effect of salt-responsive ion valves	brackish water/ different salt concentrations	channel-controlled transport at low salinity and ion valve-controlled transport at high salinity
14	(Nabizadeh *et al*., 2023)	Influence of ozone supply mode and aeration on photocatalytic ozonation of organic pollutants in wastewater using TiO2 and ZnO nanoparticles	-	the removal of organic dyes from aqueous solutions	The addition of ozone was found to enhance both the color degradation and mineralization rates of the pollutants, with intermittent ozonation proving more effective than continuous ozonation.
15	(Cheng *et al*., 2023)	Tailored ultra-low pressure nanofiltration membranes for advanced drinking water treatment	an ultra-permeable NF membrane	natural surface water, ground water, organic matter, and hardness	The optimized NF membrane (NFM-0.2) showed 95.1 % Na_2SO_4 rejection while maintaining superior antifouling behaviors. During the filtration of natural surface water, NFM-0.2 presented 75.5 % higher removals of DOC, UV_{254}, and bisphenol A. The application of NFM-0.2 for filtrating ground water indicated that NFM-0.2 could remove 50.0 % and 62.9 % of organic matter and total hardness, respectively.
16	(Qu *et al*., 2022)	Graphene Oxide Nanofiltration Membrane Based on Three-Dimensional Size-Controllable	zeolite imidazole framework-8 (ZIF-8) nanoporous material embedded in a GOM	water treatment and dye separation	The separation and permeability of the composite nanofiltration membrane significantly improve.

No.	references	Title of Project	Filtration types	Filter application	Results
		Metal-Organic Frameworks for Water Treatment			
17	(Zhang *et al*., 2022)	Leaf-veins-inspired nickel phosphate nanotubes-reduced graphene oxide composite membranes for ultrafast organic solvent nanofiltration	ultrafast organic solvent nanofiltration	OSN	The in-situ synthesized NPTs intercalation and crosslinking benefit the robust, thin, and continuous NPTs-rGO membrane.
18	(Jin *et al*., 2022)	A novel organic solvent nanofiltration (OSN) membrane fabricated by Poly(m-phenylene isophthalamide) (PMIA) under a large-scale and continuous process	OSN fabricated by PMIA	industrial scale-up	at similar rejection (100%) the methanol and acetonitrile permeance increased dramatically at 10 and 5 times than current commercial OSN membranes.
19	(El-Zahhar *et al*., 2022)	Development of Composite Thin-Film Nanofiltration Membranes Based on Polyethersulfone for Water Purification	novel thin-film composite NF membranes	rejection of crystal violet dye	The rejection of Na2SO4 and $MgCl_2$ increased with increasing MMT content and reached 96% and 35.4%, respectively.
20	(Gul *et al*., 2023)	Efficient photodegradation of methyl red dye by kaolin clay supported zinc oxide nanoparticles with their antibacterial and antioxidant activities	-	methyl red, Citrobacter, and Providencia	The results acquired from photodegradation analyses show that ZnO NPs and ZnO/KC NCs degraded about 90 and 99% of MR dye respectively.
21	(Alghamdi *et al*., 2022)	Magnetite nanoparticles-incorporated composite thin-film nanofiltration membranes based on cellulose nitrate substrate	Thin-film composite nanofiltration membranes	Na2SO4 and NaCl rejections/ water desalination and treatment	Na2SO4 and NaCl rejections increased with increasing MNPs content, reaching, respectively, 96.8% and 76.6% at 0.1 wt% MNPs content
22	(Wang *et al*., 2022)	Transport properties of graphene oxide nanofiltration membranes: Electrokinetic modeling and	GO and rGO membranes	water and unary aqueous solutions/ high salt rejections	Such models will be useful in accelerating structure-separation property relationships of GO membranes and for separation process design and optimization.

No.	references	Title of Project	Filtration types	Filter application	Results
		experimental validation			
23	(Ali *et al*., 2022)	Magnetically active nanocomposite aerogels: preparation, characterization and application for water treatment	-	removal of dyes in water	The sorption capacity of the aerogels was 1501 and 1390 mg/g within 10 min for methyl blue and methyl orange dyes, respectively; confirming very fast removal capacities.
24	(Marjani *et al*., 2020)	Effect of graphene oxide on modifying polyethersulfone membrane performance and its application in wastewater treatment	Polyethersulfone (PES) nanocomposite membranes	salt rejection, dye retention and heavy metals removal	The experimental results corroborated that the addition of GO to the membrane significantly improved the pure water flux, salt rejection, and heavy metals removal.
25	(Ang *et al*., 2020)	Improved performance of thin-film nanofiltration membranes fabricated with the intervention of surfactants having different structures for water treatment	thin-film composite nanofiltration polyamide	rejection of divalent ions/salt	It is exhibited high rejections of divalent salts (RNa2SO4 = 92.26 ± 3.30%; RMgSO4 = 93.83 ± 3.22%; RMgCl2 = 94.15 ± 2.52%).
26	(Heidari *et al*., 2023)	Improvement of salt rejection efficiency of cellulose acetate membrane through modification by poly(amidoamine) dendrimer-functionalized graphene oxide	cellulose acetate membrane	Na_2SO_4, NaCl and $MgCl_2$	Based on the data found, adding the filler improves membrane properties.
27	(Liu *et al*., 2021)	Using loose nanofiltration membrane for lake water treatment: A pilot study	a loose NF membrane	a sand filtration effluent	Results showed that the membrane demonstrated a high rejection of TOC (by<90%) and a moderately high rejection of two pesticides (54%–82%) while a moderate rejection of both calcium and magnesium (~45%) and a low rejection of total dissolved solids (~27)
28	(Cheng *et al*., 2021)	Finely tailored pore structure of polyamide nanofiltration membranes for highly-efficient	polyamide nanofiltration membrane	Inorganic salts, dyes, printing and dyeing industry, and metallurgy and mining industry	Interestingly, the membranes exhibit excellent performance for dye separation (rejection greater than 98%) and molecular weight cut-off

No.	references	Title of Project	Filtration types	Filter application	Results
		application in water treatment			(MWCO) of about 554.34 Da under the optimum separation conditions.
29	(Song *et al*., 2021)	Tailoring nanofiltration membrane with three-dimensional turning flower protuberances for water purification	Three-dimensional flower nanofiltration membrane	different salt solutions under different pressures	The more MIL-101(Cr) nanomaterials are added, the more protuberances. The separation performance of PA-flower membrane from high to low is RMgSO4 > RNa2SO4 > RMgCl2 > RNaCl, and the $RMgSO_4$ and RNa2SO4 can reach 97.13% and 88.27.% at 0.75 MPa.
30	(Mamun Kabir *et al*., 2022)	Recovery of dyes and salts from highly concentrated (dye and salt) mixed water using nano-filtration ceramic membranes	The commercial nano filtration ceramic membrane	highly concentrated (dye and salt) mixed water, NaCl and Na2SO4	Pollutant removals were achieved with noteworthy values for the chemical oxygen demand for permeate solution also a color difference between concentrate and permeate. In conclusion, the strong rejection of dyes by the NF ceramic membranes proves that they can be a suitable alternative for the textile wastewater treatment processes.
31	(Peng *et al*., 2019)	Surface modified polyamide nanofiltration membranes with high permeability and stability	piperzine-trimesoyl chloride (PIP-TMC) polyamide nanofiltration membranes	Salt rejection	The PIP-TMC-QAEP membrane exhibits high salt rejection (RNa2SO4 = 97.8%, RMgSO4 = 94.2%).
32	(Wei *et al*., 2021)	Preparation of graphene oxide/polyamide composite nanofiltration membranes for enhancing stability and separation efficiency	Polysulfone (PS) hollow fiber ultrafiltration (UF) membrane	salt solutions/ dye molecule rejection	The GO/PA-NF membrane showed a high flux (48 L/m^2h) and rejection rate (96.9%). The GO/PA-NF membranes could reject dye molecules effectively, and the rejection rates for Congo red and cationic red X-GTL were 100% and 99.8%
33	(Zhang *et al*., 2022)	Improving stability and separation performance of graphene oxide/graphene nanofiltration membranes by adjusting the laminated regularity of stacking-sheets	The laminated graphene oxide (GO) membranes	Methylene blue, Congo red, Rhodamine B and Methyl orange rejection	Compared with the pure GO membranes, GO/Gr-0.5 membranes exhibited a higher Na_2SO_4, NaCl, $MgCl_2$, and $MgSO_4$ rejection. Meanwhile, the rejection rate (99.5%, 99.9%, 97.3%, and 98.6%) of composite membranes for Methylene blue, Congo red, Rhodamine B, and Methyl

No.	references	Title of Project	Filtration types	Filter application	Results
					orange could be achieved.
34	(Qin *et al*., 2020)	Design of a novel interfacial enhanced GO-PA/APVC nanofiltration membrane with a stripe-like structure	New-style thin film composite nanofiltration (TFC NF) membrane with a stripe-like surface structure/ The aminated polyvinyl chloride (APVC) membrane	salt rejection	The water permeability of the GO-PA/APVC membrane was improved by more than 60% while the salt rejection remained stable compared with PA/APVC membrane.
35	(Priyadarshini *et al*., 2020)	Skinned carbonaceous composite membrane with pore channels bearing an anchored surfactant layer for nanofiltration	a specific surfactant pair appended to the nanopores in a skinned carbonaceous composite membrane (CnCM)	An aqueous methylene blue (MB) solution (50 mg/L)	Softening the internal pore surface of CnCM by the adsorption of a surfactant layer offers a tactic for utilizing a porous carbon medium different from the traditional CMS membrane to conduct nanofiltration of liquid solutions.
36	(Evdochenko *et al*., 2020)	Unraveling the effect of charge distribution in a polyelectrolyte multilayer nanofiltration membrane on its ion transport properties	Polyelectrolyte (PE) multilayer nanofiltration membranes	the rejection of symmetric and asymmetric salts	The model enables to formulation of an effective charge distribution for different polyelectrolyte multilayer (PEM) structures.
37	(Han & Wu, 2019)	High-performance graphene oxide nanofiltration membrane with continuous nanochannels prepared by the in situ oxidation of MXene	novel GO-based nanofiltration membrane intercalated with TiO2 nanoparticles	four different organic dyes	The rejection rate for four different organic dyes is above 97%. The highly improved water permeability with no obvious sacrifice of rejection rate was attributed to the presence of continuous nanochannels obtained via the in situ oxidation of MXene without destroying the intrinsic stacking structure of GO sheets.
38	(Zhao *et al*., 2019)	High flux nanofiltration membranes prepared with a graphene oxide homo-structure	High flux nanofiltration (NF) membranes with a unique homo-structure	dye macromolecules, proteins, natural organic matters, and metal nanoparticles (NPs)	With GO QDs, the permeability of the membranes was markedly improved in all the testing solutions (2–4 times) without compromising their retention for direct yellow, bovine serum albumin, humic acid, and Au NPs (>99%).
39	(Lee *et al*., 2019)	A surface-modified EDTA-reduced graphene oxide membrane for nanofiltration	Surface-modified EDTA-reduced graphene oxide membranes	For monovalent ions	The resulting P-EDTA-rGO membrane demonstrated rejection rates of more than 80% for NaCl.

No.	references	Title of Project	Filtration types	Filter application	Results
		and anti-biofouling prepared by plasma post-treatment			
40	(Mahalingam *et al*., 2019)	Stable Graphene Oxide Cross-Linked Membranes for Organic Solvent Nanofiltration	stable ethylenediamine-cross-linked GO membranes	organic solutions containing molecular dyes	The prepared membranes with a 150 nm thickness demonstrated high permeance for water and organic solvents and exhibited a rejection >95% for small organic dyes dissolved in methanol.
41	(Liu *et al*., 2019)	Post-synthesis of a covalent organic framework nanofiltration membrane for highly efficient water treatment	a highly stable covalent organic framework (COF) IISERP-COOH-COF1 membrane	Ion rejection	Demonstrated by both experimental and simulation studies, the IISERP-COOH-COF1 membrane shows superior ion rejection.
42	(Zhang *et al*., 2018)	A multifunctional graphene-based nanofiltration membrane under photo-assistance for enhanced water treatment based on layer-by-layer sieving	a photo-assisted multifunctional NF membrane	dye rejection/ salt ions/ removal of ammonia, antibiotic, and bisphenol A	Benefiting from the photo-assistance, our NF membranes show an enhanced water flux (~16 L m−2 h−1 bar−1), while keeping a high dye rejection (~100% for Methyl Orange).
43	(Gao *et al*., 2018)	Enhanced stability and separation efficiency of graphene oxide membranes in organic solvent nanofiltration	GO membranes crosslinked with boronic acid polymer (BA)	organic solvent nanofiltration (OSN)/ rejection for acid fuchsin (AF) methanol solution	The rejection for acid fuchsin (AF) methanol solution of the GO membrane was increased by 20.7%. The optimized membrane maintained high rejection (95.8%) for AF methanol solution with a slight compromise in methanol permeance. Moreover, the composite membrane exhibited high rejections for both EB and AF in harsh DMF solvent.
44	(Chen *et al*., 2018)	A large-area free-standing graphene oxide multilayer membrane with high stability for nanofiltration applications	A flexible and free-standing graphene oxide and nylon 6 multilayer nanofiltration membrane	organic dye rejection/ rejection of the Na_2SO_4, NaCl, $CuSO_4$, and $Pb(NO_3)_2$	The novel GO@nylon 6–13 multilayer nanofiltration membrane demonstrated a high organic dye rejection rate (>95% for methylene blue, and >99% for methyl orange). The rejections rate of the Na_2SO_4, NaCl, CuSO4, and $Pb(NO_3)_2$ were 56.5%, 27.6%, 36.7%, and 18.9%, respectively.
45	(Chen *et al*.,	High-performance	graphene oxide nanofiltration	Organic dye/ salt	The GO (120) NFM

No.	references	Title of Project	Filtration types	Filter application	Results
	2018)	graphene oxide nanofiltration membrane prepared by electrospraying for wastewater purification	membrane (GO NFM)	ion rejection	demonstrated a high organic dye rejection rate (98.88%, 98.97%, 100%, and 99.99%, for BF, MB, MO, and EB, respectively).
46	(Mahalingam *et al.*, 2018)	Graphene Oxide Liquid Crystal Membranes in Protic Ionic Liquid for Nanofiltration	Graphene oxide liquid crystal membranes	rejection of dyes	Robust membranes with GO layers as thick as 1 μm with high permeance (37 L/(m2 h bar)) and 99.9% rejection of dyes with molecular weight 697 g/mol were obtained.
47	(Zaman *et al.*, 2018)	Polyimide-graphene oxide nanofiltration membrane: Characterizations and application in enhanced high concentration salt removal	polyimide (PI)/graphene oxide (GO) mixed matrix membrane	diluted and concentrated salt solutions	Results showed that the MMM possesses nanofiltration (NF) properties with high water permeability and excellent salt rejection (99%) in diluted conditions regardless of the applied filtration pressure.
48	(Yu *et al.*, 2021)	The intercalation of nanoscale lattices into micro-sized graphene oxide sheets for enhancing pressure-driven desalination performances	Graphene oxide-based nanofiltration membranes (GONMs)	MgCl2, NaCl, MgSO4 and Na2SO4 rejection/ dye rejection	As a result, the regulated membrane improves the rejection rates of $MgCl_2$, NaCl, $MgSO_4$, and Na_2SO_4 up to 41.10%, 64.14%, 84.62%, and 93.19%, respectively, compared to unregulated counterparts of 13.72%, 15.93%, 34.58%, and 40.99%, respectively
49	(Akbari *et al.*, 2018)	Solvent Transport Behavior of Shear Aligned Graphene Oxide Membranes and Implications in Organic Solvent Nanofiltration	Graphene oxide (GO) membrane	methyl red/ Rose Bengal/ RhodamineB/ Organic Solvent	As a result of this polar interaction, the permeance of polar solvents in GO membrane scales inversely to the polarity of the solvent, which is contrary to other polymeric and ceramic hydrophilic membranes and also scales inversely to the viscosity of solvents as per continuum expectations.
50	(Epsztein *et al.*, 2018)	Role of Ionic Charge Density in Donnan Exclusion of Monovalent Anions by Nanofiltration	commercial polyamide NF270 membrane	four monovalent anions—fluoride (F–), chloride (Cl–), bromide (Br–), and nitrate (NO3–)	In the solutions containing F– and Cl– or F– and Br–, F– rejection was higher than Cl– or Br– rejection only when the solution pH was higher than 5.5, suggesting that F– (which has a higher charge density) was repelled more strongly by the negatively charged membrane.

No.	references	Title of Project	Filtration types	Filter application	Results
51	(Déon *et al*., 2018)	Application of a new dynamic transport model to predict the evolution of performances throughout the nanofiltration of single salt solutions in concentration and diafiltration modes	A tubular thin film polyamide membrane	salt solution/ ion rejection	This model was found to predict accurately the filtration performances with various salts whether the filtration is performed in concentration or diafiltration modes.
52	(Chang *et al*., 2017)	Fabrication of the reduced preoxidized graphene-based nanofiltration membranes with tunable porosity and good performance	reduced preoxidized graphene membranes	Dye/ salt ion rejection	The membranes were able to maintain a high dye rejection (>97.5% for methyl orange (MO)) and a good rejection ratio for salt ions (71.2% for MgSO4).
53	(Shen *et al*., 2017)	Tuning inter-layer spacing of graphene oxide laminates with solvent green to enhance its nanofiltration performance	the laminar GO membranes	dye molecules	It was found from the results that the SG@GO composite membranes showed a flux of 330 L m−2 h−1 MPa−1, which was nearly 6-fold enhancement compared with that of the pristine GO membrane (56 L m−2 h−1 MPa−1), without sacrificing the dye rejection.
54	(Yuan *et al*., 2017)	Enhanced desalination performance of carboxyl functionalized graphene oxide nanofiltration membranes	Graphene oxide (GO) and carboxyl functionalized graphene oxide (GO-COOH) membrane	Salt rejection	The results showed that GO-COOH membranes exhibited not only higher permeability but also better salt rejections compared with pristine GO membranes.
55	(Gao *et al*., 2017)	Graphene membranes with tuneable nanochannels by intercalating self-assembled porphyrin molecules for organic solvent nanofiltration	reduced graphene oxide (rGO) membranes intercalated with self-assembled 5, 10, 15, 20-tetrakis (1-methyl-4-pyridinio) porphyrin (TMPyP) molecules	Dye rejection in either water or methanol	This composite membrane exhibited high rejection (>92%) for negatively charged organic dyes with molecular dimensions larger than 1.7 nm in methanol. As a demonstration, it was used to separate vitamin B12 from its aqueous or methanol solution, a rejection of 98.4% or 91.0%.
56	(Xing *et al*., 2017)	Shaping nanofiltration channels in a carbonaceous	The carbonaceous membranes (CnMs)	methylene blue	The NF of an aqueous solution of methylene blue (MB, 10 ppmw) is utilized to assess these CnMs to

No.	references	Title of Project	Filtration types	Filter application	Results
		membrane: Via controlling the pyrolysis atmosphere			show the impacts of the NCs on the separation performance.
57	(Rashid *et al.*, 2017)	Nanofiltration applications of tough MWNT buckypaper membranes containing biopolymers	self-supporting carbon nanotube membranes	BPs towards water, inorganic salts, and dissolved trace organic contaminants (TrOCs), such as pharmaceuticals, personal care products, and pesticides	Of the twelve TrOCs investigated in this study, nine were rejected by more than 95% by BPs composed of MWNTs and chitosan. The latter BPs also demonstrated good rejection of both NaCl (30–55%) and $MgSO_4$ (40–70%).
58	(Wang *et al.*, 2017)	Toward the fabrication of advanced nanofiltration membranes by controlling morphologies and microchannel orientations of hexagonal lyotropic liquid crystals	mesoporous membrane templated from hexagonal LLC	Salt rejection	.This review presents the current progress on the strategies for structure retention from a hexagonal LLC template and the up-to-date techniques used for the reorientation of mesochanels for continuity through the whole membrane.
59	(Zhang *et al.*, 2017)	Graphene Oxide Quantum Dots Incorporated into a Thin Film Nanocomposite Membrane with High Flux and Antifouling Properties for Low-Pressure Nanofiltration	thin film nanocomposite (TFN) membranes comprising GOQDs dispersed within a tannic acid (TA) film	dye rejection	The TA/GOQDs TFN membrane showed a pure water flux up to 23.33 L/m2·h (0.2 MPa), which was 1.5 times more than that of pristine TA TFC membrane, while high dye rejection to Congo red (99.8%) and methylene blue (97.6%) was kept.
60	(Akbari *et al.*, 2016)	Large-area graphene-based nanofiltration membranes by shear alignment of discotic nematic liquid crystals of graphene oxide	Graphene-based membranes	Methyl Red rejection	The highly ordered graphene sheets in the plane of the membrane make organized channels and enhance the permeability (71±5 l m−2 hr−1 bar−1 for 150±15 nm thick membranes).
61	(Zhu *et al.*, 2016)	Single-Walled Carbon Nanotube Film Supported Nanofiltration Membrane with a Nearly 10 nm Thick Polyamide Selective Layer for High-Flux and High-Rejection Desalination	Single-Walled Carbon Nanotube Film Supported Nanofiltration Membrane	Desalination/ divalent ions	The obtained NF membrane exhibits an extremely high performance with a permeating flux of 32 L m−2 h−1 bar−1 and a rejection rate of 95.9% to divalent ions. This value is two to five times higher than the traditional NF membranes with a similar rejection rate.

No.	references	Title of Project	Filtration types	Filter application	Results
62	(Nam *et al*., 2016)	Enhanced Stability of Laminated Graphene Oxide Membranes for Nanofiltration via Interstitial Amide Bonding	Laminated graphene oxide (GO) membrane with polymer support with branched polyethylene-imine (prepared GO/BPEI membranes)	dye molecules methylene blue, rose bengal, and brilliant blue	BPEI treatment did not affect the filtration performance of the GO film, as evidenced by the high rejection rates (>90%) for the dye molecules methylene blue, rose bengal, and brilliant blue and by their permeation rates of ca. 124, 34.8, 12.2, and 5.1%, respectively, relative to those of a typical GO membrane.
63	(Wang *et al.*, 2016)	Graphene oxide poly piperazine-amide nanofiltration membrane for improving flux and anti-fouling in water purification	facile polypiperazine-amide (PPA) composite nanofiltration (NF) membrane	salt rejection	The high salt rejection was still retained in the order of Na2SO4 (98.2%) > MgSO4 (96.5%) > NaCl (56.8%) > MgCl2 (50.5%).
64	(Nicolini *et al*., 2016)	Selective rejection of ions and correlation with surface properties of nanofiltration membranes	Three negatively charged commercial NF membranes (NP010, NP030, and NF90)	The rejection of salts typically present in seawater (NaCl, Na_2SO_4, $MgSO_4$, K_2SO_4, and $CaSO_4$)	NP010 and NP030 showed that high sulfate exclusion leads to an increase in the rejection of all cations present in the solution. Conversely, for NF90 membrane steric effects are predominant, and high sulfate rejection leads to a reduction of monovalent ions rejection.
65	(Yao *et al.*, 2022)	Fabrication of organic solvent nanofiltration membrane using commercial PVDF substrate via interfacial polymerization on top of metal-organic frameworks interlayer	commercial PVDF microfiltration	the pharmaceutical industry for drug concentration and organic solvent recovery	The optimal TFC membrane also showed excellent OSN performance towards various organic solvents. Furthermore, the concentration test of erythromycin in a methanol solution indicated that the PVDF/i-Cu-TCPP/PA membrane has great potential in the pharmaceutical industry for drug concentration and organic solvent recovery.
66	(Gu *et al.*, 2021)	Surface-crumpled thin-film nanocomposite membranes with elevated nanofiltration performance enabled by facilely synthesized	COF-based thin-film nanocomposite (CTN) membranes (covalent organic framework)	rejection of charged solutes/ anionic salts	The optimal membrane showed high rejections of Na_2SO_4 and $MgCl_2$ (98.9% and 94.2%, respectively).

No.	references	Title of Project	Filtration types	Filter application	Results
		covalent organic frameworks			
67	(Yang *et al.*, 2020)	A polyamide membrane with tubular crumples incorporating carboxylated single-walled carbon nanotubes for high water flux	COOH-SWCNT/NF membranes (Carboxylated single-walled carbon nanotubes (COOH-SWCNT))	rejection of salt	The rejection of Na_2SO_4 and $MgSO_4$ were 95.69% and 90.03%, respectively. These excellent results were achieved using low loadings of nanofillers and under relatively low pressure (3.5 bar).
68	(Zhu *et al.*, 2021)	Crumple-textured polyamide membranes via MXene nanosheet-regulated interfacial polymerization for enhanced nanofiltration performance	The MXene-interlayered NF membranes	saline water desalination and advanced treatment of drinking water	Excellent water permeability of 27.8 ± 2.1 L m−2 h−1 bar−1 together with satisfactory α($NaCl/Na_2SO_4$) of ~480 was obtained for the MXene-interlayered NF membrane, overcoming the trade-off effects between water permeance and salt selectivity.
69	(Singhal *et al.*, 2020)	Development of super hydrophilic tannic acid-crosslinked graphene oxide membranes for efficient treatment of oil-contaminated water with enhanced stability	oleophobic and super-hydrophilic graphene-based membrane	oil-contaminated water	The membranes exhibited a significant reduction in the values of chemical oxygen demand (COD), total dissolved solids (TDS), total suspended solids (TSS) and turbidity demonstrating low-oil adhesion and preferable oil rejection rates. In such a way, TA crosslinked GO membranes present a robust and efficient way to treat oil-contaminated water released from various industries which can be reused for numerous further applications.

- *Manufacturing Methods and Modification Techniques of Nanofiltration*

NF membrane technology is commonly used in water treatment, the food and beverage industry, the pharmaceutical industry, chemical, and textile industry. It is also used in emerging applications such as agriculture (salinity reduction and wastewater treatment) and environmental protection (wastewater treatment, nutrient recovery). For NF usage, it is estimated that the Water treatment segment accounts for a range of 50-60% because of its effectiveness in treating brackish water and a large variety of industrial and municipal water streams; the Food and Beverage Industry holds the second share of nanofiltration application fluctuated between15 and 20 percent and other industries are approximately 20-30%. Above all, it should be highlighted that this estimation is based on available information.

- ***Manufacturing Methods***

There are some manufacturing methods generally used for building nanofiltration: Interfacial Polymerization, Phase inversion, Electrospinning, and Track etching. First, Interfacial polymerization is based on the reaction of two monomers at an interface to create a thin selective layer on a porous support material. Second, Phase inversion is the method of casting a polymer solution and involving phase separation to generate a membrane with a porous structure (Putri and Munasir, 2020) (Vargas-Figueroa *et al.*, 2023). Third, the solution electrospinning technique involves the fabrication of electrospun nanofiber membranes (ENMs). Electrospinning is a process that generates nanofibers with a large specific surface area, selective wettability, and interconnected pore structure. ENMs can also be modified to enhance their filtration performance. (Dmitrenko *et al*., 2023). Lastly, Track etching is a conventional method used to fabricate membranes, but it is not as superior as electrospinning for nanofiber membrane production. Track etching involves bombarding a polymer membrane with high-energy particles, such as ions or electrons, to create tracks or pores in the membrane. The size and shape of the pores can be controlled by adjusting the energy of the bombarding particles and the etching conditions. It is commonly used to fabricate porous membranes with well-defined pore sizes and distributions. However, electrospinning is considered a more effective method for fabricating nanofiber membranes due to their superior mechanical properties and high porosity (Kardel *et al.,* 2023). Additionally, post-treatments such as coatings and grafting can be applied to more porous support to enhance the performance of NF membranes and Layer-by-layer coatings, aquaporin incorporation, and the use of glassy polymers with high internal porosity are emerging technologies being explored for NF membrane fabrication (Vargas-Figueroa *et al*., 2023).

- ***Modification Techniques***

Modifying commercial NF membranes involves enhancing their permeability and selectivity by introducing modifications to the membrane surface. One approach to modify NF membranes is by attaching carbon nanotubes (CNTs) to the polymeric surface using microwave-assisted in-situ growth. The modified NF membranes, such as NF270-Ppy-CNT, show improved ion rejection performance compared to unmodified membranes. (Dmitrenko *et al*., 2023). Moreover, NF membranes can be modified using interpenetrating polymer networks to improve their performance. Different polymers and monomers can be used for modification, such as [3-(acryloyl amino)propyl]trimethylammonium chloride (ClAPTA), 2-acrylamide-2-methyl-1-propanesulfonic acid (APSA), and glycidyl methacrylate-N-methyl-d-glucamine (GMA-NMG). The modified membranes can exhibit changes in surface topography and roughness, depending on the specific modifications applied. The best modifications can lead to significant improvements in water flux and chloride rejection compared to commercial membranes, without sacrificing high rejections of other species (Kardel *et al*., 2023). One approach is the bulk modification of the membrane by introducing graphene oxide (GO) into the polymer matrix. Another approach is the surface modification of the membrane using the layer-by-layer (LbL) technique. This involves the deposition of polyelectrolyte (PEL) layers onto the membrane surface. Different combinations of PELs, such as polydiallyldimethylammonium chloride-polyacrylic acid (PAA), polyethyleneimine (PEI)-PAA, and polyallylamine hydrochloride-PAA, can be used. The number of PEL bilayers deposited by the LbL method also affects the properties of the membrane. The combined use of bulk and surface modifications has been shown to significantly improve the rejection of dyes (Sardrood, 2023). On the other hand, nanofiltration membranes can be modified and manufactured using the layer-by-layer procedure, which involves depositing polyelectrolyte layers on a support material. The layer-by-layer process allows for the adjustment of various parameters to optimize the properties of the resulting nanofiltration membrane. Polyelectrolyte multilayer (PEM) membranes, produced through this process, offer significant improvements in chemical resistance, fouling resistance, and selectivity compared to traditional thin film composite (TFC NF) membranes (Kardel *et al.*, 2023). The modified PAN membranes exhibited excellent potential for oily wastewater purification at low oil concentrations at 10 ppm when compared with the pristine PAN membranes. This could be due to the following exceptional properties they exhibited: high separation efficiency, resistance to oil fouling, and outstanding environmental durability (Sardrood, 2023).

Results and Discussion

Discharging a large amount of wastewater from the food industries, especially the dairy industry is a crucial environmental problem. This wastewater poses serious environmental challenges if not treated properly. Conventional treatment methods often fail to meet discharge quality standards due to high organic loading and variability in wastewater composition. Recent advancements in membrane-based processes, particularly those utilizing nanomaterials, show promise for improving wastewater reuse and recycling. Even though some problems, such as fouling remained challenging, improving membranes by utilizing nanoparticles synthesized by state-of-the-art methods like green synthesis hold these problems back and attain high-quality water. To summarize, on account of water shortage and possible dangers of contaminated water, taking an innovative approach such as membrane-based water and wastewater treatment may be our best hope in the long term, and certainly, NF membranes are a clear-cut answer for the crucial problem of global water shortage, contributed to produce high-quality drinking water and reusing wastewater at a lower cost in comparison with reverse osmosis and similarly, it should be noted that NF is adequately able to separate the smaller molecules than ultrafiltration membrane. Therefore, using NF can lead to low costs, high-efficiency separation, more fresh water, reduction of chemical and microbial pollution, and nutrient recovery in food industry wastewater such as fats and proteins, resulting in a remarkable increase in the quality of human life.

Conclusion

Based on previous studies, the food industry wastewater is considered to be one of the serious threats due to the discharge of numerous types of pollutants into the water bodies, while dairy industries are among the major sectors in the food industry generating high volumes with high organic content wastewater, having a high level of nutrients and lipids. This, in turn, may cause serious ecological consequences; hence, water and wastewater recycling in the field becomes a very crucial question at this point, where nanofiltration membrane technology has an important role in water and wastewater treatment. Nanofiltration membranes have been widely applied because the application of reverse osmosis membranes leads to very high costs. Nanofiltration membranes can decompose soluble particles efficiently due to their capabilities for the removal of organic substances and reducing water hardness; hence, they are suitable for application in water with low total dissolved solids, such as surface water. The application of nanofiltration membranes is important not only in the desalination of industrial regions but also in the treatment of water and wastewater, given that such areas retain a wide variety of ions along with organic elements seriously threatening environmental integrity. Population growth, climate change, industrial development, and world water shortage all create intractable problems related to water supplies that the global community is facing; nanofiltration technology can be applied suitably. Emphasis on the development and implementation of advanced technologies such as nanofiltration, and the production of nanocomposite membranes that ensure higher permeability, better selectivity, and better antifouling properties, especially through greener synthesis, is one of the promising lines for overcoming the problems in the treatment of wastewater from the food industry, more precisely from the dairy sector. Future studies should place their focus on the development of new membrane material incorporation, economic alternatives, and environmentally friendly synthesis techniques that can be used in fabricating advanced membranes with higher water flux, optimized rejection, and reduced membrane fouling and lower negative impacts on the environment.

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