Review

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Separation of Organic Carbon and Nutrients from Liquid Waste by Using Membrane Technologies

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Abstract

The increasing generation of liquid waste from agricultural, industrial, and municipal sources poses significant environmental challenges due to its high content of organic carbon (OC) and nutrients such as phosphorus and nitrogen. This review examined the effectiveness of membrane-based technologies, particularly microfiltration (MF) and ultrafiltration (UF), in separating and recovering these valuable compounds. Drawing on key literature indexed in Scopus, the review analyzed how membrane properties, operating conditions, and feed characteristics influence removal efficiency. The findings indicate that MF membranes primarily retain particulate organic matter and suspended solids (SS), with limited retention of phosphorus and nitrogen species. In contrast, UF membranes exhibited superior performance in removing both OC and phosphorus, and partially retain some nitrogen compounds depending on molecular size and charge. When combined with pre-treatment processes such as coagulation or adsorption, both MF and UF achieve higher nutrient removal rates. These membrane technologies showed promise not only in reducing pollutant loads but also in enabling nutrient recovery for potential reuse in agriculture. The optimization of membrane configuration and integration with other processes is essential for enhancing treatment performance and contributing to circular wastewater management strategies.

Keywords: microfiltration; nutrients; organic carbon; removal efficiency; ultrafiltration

1. Introduction

The growing global demand for water and the increasing generation of wastewater from domestic, industrial, and agricultural sources have intensified the need for efficient and sustainable treatment technologies [1–3]

Liquid waste streams often contain significant concentrations of OC and nutrients such as nitrogen and phosphorus, which, if not properly managed, contribute to serious environmental issues including eutrophication, groundwater contamination, and greenhouse gas emissions [4,5]. Conversely, these waste streams also represent a valuable source of recoverable materials that could be reused in agriculture and industry, supporting the principles of circular economy and resource recovery [6–8]. Conventional wastewater treatment methods, including biological and chemical processes, have proven effective in many cases but often present limitations such as high energy consumption, sludge generation, and incomplete removal of certain pollutants [9]. Among the advanced treatment options, membrane technologies especially pressure-driven MF and UF have gained attention due to their operational efficiency, modularity, and ability to selectively separate particulate and colloidal matter based on size exclusion mechanisms [10,11]

MF and UF membranes differ in pore size and separation performance, with MF typically removing particles >0.1 micrometer (μm) and UF targeting smaller solutes, including macromolecules and certain nutrient forms [12,13]. These membranes can effectively retain OC

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compounds and, to a certain extent, phosphorus and nitrogen species, depending on membrane material, configuration, and operational parameters [14–16]. Additionally, integrating MF and UF with pre- or post-treatment techniques such as coagulation, adsorption, or biological processes enhances the removal efficiency of nutrients, making these technologies suitable for both centralized and decentralized treatment systems [11,17]. This review aims to provide a comprehensive overview of the performance of MF and UF membranes in the separation of OC and nutrient compounds from liquid waste. The emphasis is placed on the influence of membrane characteristics, feed composition, and operational conditions on the separation efficiency. The objective is to highlight the advantages and limitations of these technologies and inform future researchers the strategies for sustainable wastewater treatment and resource recovery.

2. Technologies for the Removal of OC and Nutrients from Wastewater

The elimination of OC and nutrients from wastewater is essential for several benefits, including preventing eutrophication of surface water bodies and recovering fertilizer and maintaining water quality [18]. According to [19], various technologies are employed to remove key nutrients like carbon, nitrogen and phosphorus from wastewater and the recovery rate varies from one technology to another (Figure 1).

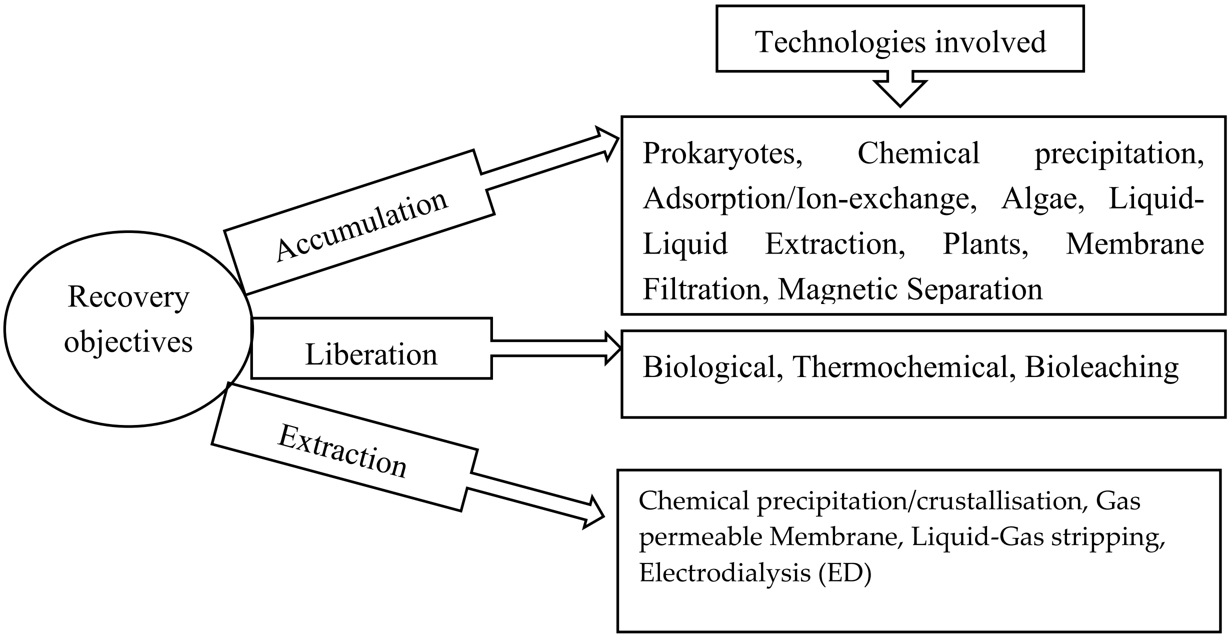

Figure 1. Technologies to remove nutrients from waste streams [20].

Membrane filtration, consisting of microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) processes finds its application when nutrient accumulation is targeted [20]. Product recovery quality depends on membrane pore size, nutrient size, feed characteristics and application pressure (Figure 2). Especially for the removal of organic substances from liquid waste, MF and UF processes are used [19,21,22]. In general, MF membranes are used to remove particles larger than 0.5 µm, whereas membrane filters with a pore size of 0.002-0.5 µm are available for UF in order to eliminate macromolecules and colloidal particles. According to [23], both two membranes are also required for filtration of viruses (0.03–1 µm) and bacteria (0.5–20 µm). MF membranes have pore sizes ranging from 0.1 to 10 µm with an applied pressure range of 0.1–2 bar from an inlet fluid stream. Globally, MF can effectively remove suspended solids (SS), particulate and colloidal organic species. However, it is less effective in removing dissolved organic, nutrients and smaller organic compounds. UF membranes have smaller pore sizes than MF ones, ranging from 0.01 to 0.1 µm [24]. They also operate via size exclusion but can retain much smaller particles, including macromolecules and some colloidal substances. UF is effective in removing a broader range of organic contaminants, including proteins, polysaccharides, and other macromolecules [25]. It can also remove some dissolved organic compounds, depending on their size. For a high efficiency, MF and UF in the removal of inorganic and organic micropollutants are applied in integrated systems coupled with coagulation, flocculation, sedimentation, adsorption, complexion with polymers or surfactants and biological reactions [28,29]. With low operating pressure in the range of 0.1-2.5 bar and pore size ranging between 0.1 and 10 µm, MF membrane have removed organic compounds until 95% by showing a permeability of 500L/m².h.bar [28]. On the other hand, with UF membrane, the same recovery was achieved by applying the pressure of 2-5 bar with 0,001-1µm of membrane pore size by showing 150L/m².h.bar of permeability. According to [31–33], the high concentration of organics such as O C is found in concentrate of MF when municipal, urban and agricultural wastewater are treated and inorganic ions remain in MF permeate. UF removes phosphorus, nitrogen, and OC in soluble and colloidal form within removal rate in the range of 10-85% [32]. Phosphorous and nitrogen in particulate form with the size > 0.1 µm can be selectively removed by those filtration processes [33].

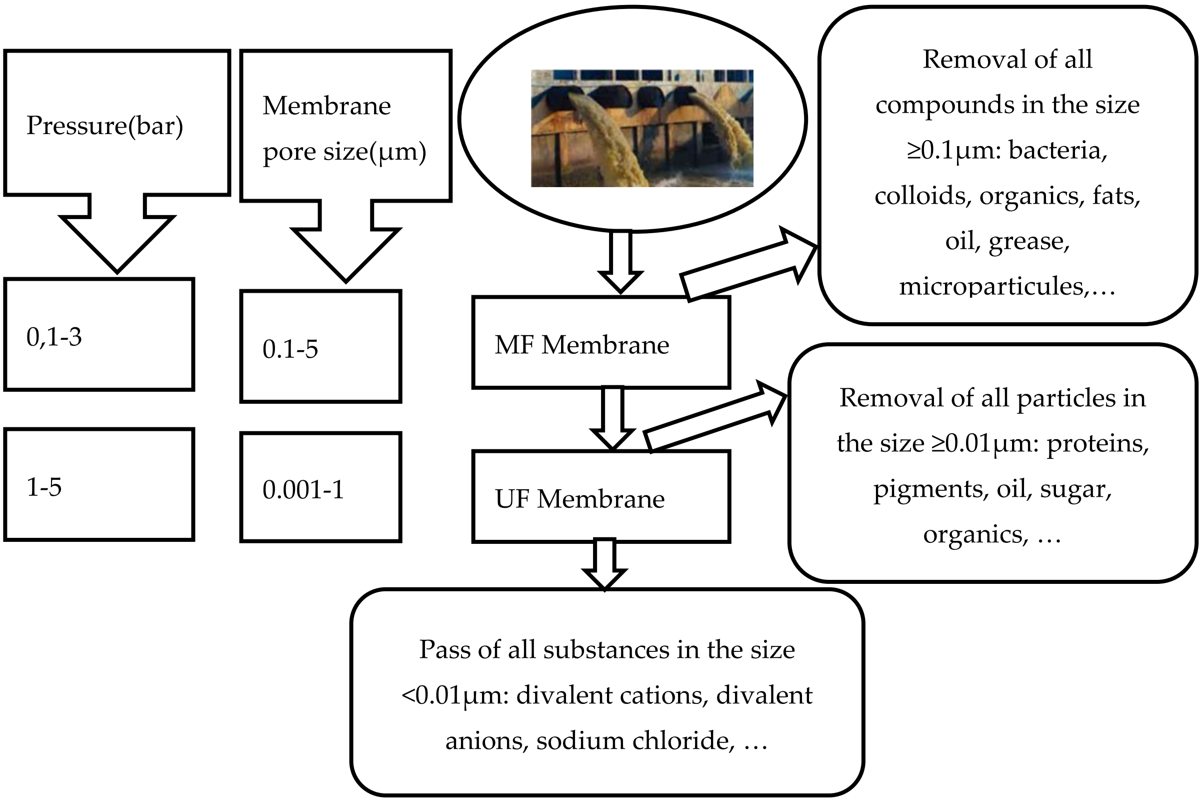

Figure 2. General features on MF and UF membranes.

In their researches, [10,31,36,37] demonstrated that organics are removed by microfiltration and ultrafiltration membranes while inorganic ions pass through the pore of each module. When MF is involved, OC is retained whereas inorganics such as phosphorus and nitrogen forms pass through the membrane pore size [36]. Inorganics separation or recovery in the UF membranes depends on the ionic charge [37]. Total nitrogen (TN) and total phosphorus (TP) dominated by particulate forms show high concentration in UF concentrate [38]. Trivalent, divalent and monovalent for instance are retained in the UF permeate [39]. This behavior also depends on the size of the components (Table 1) and membrane solute permeability.

Table 1. Size of nutrients from wastewater.

Component	Nutrients	Nutrients form	Size(µm)	References
Organics	Organic Carbon	TOC	1-100 µm	[40]
Inorganics	Nitrogen	TN	>0.5 nm	[41]
		Ammonium ion (NH_4^+)	0.1 to 0.5 nm	
		Nitrate (NO_3^-)	0.2 to 0.4 nm	
		Nitrite (NO_2^-)	0.2 to 0.4 nm	
	Phosphorus	TP	higher than 0.5nm	
		Phosphate (PO_4^{3-})	0.5 nm in diameter	

2.1. Removal Efficiency of OC from Liquid Waste by Using MF Membrane

In the context of assessing the removal efficiency of OC from liquid waste, MF emerges as a promising option, offering distinctive operational advantages and limitations [42]. By harnessing a combination of physical sieving and adsorption mechanisms, this approach has demonstrated effectiveness in removing organic carbon from liquid waste [46,47]. The process mainly depends on the pore size, which is usually between 0.1 and 10µm. This helps to physically separate particulate organic matter from the liquid phase [45]. The liquid waste passes through the membrane, particles that are too big to fit through the holes in the membrane are caught on the surface or inside the holes in the membrane matrix[46]. This makes the water clearer and removes a lot of the suspended organic carbon [47]. As shown in Table 2, how well microfiltration works at removing organic carbon depends on a few things, like what the feed water is like and how the system is running [47,51]. Membrane material also significantly impacts removal efficiency [49]. Materials such as polyvinylidene fluoride (PVDF), polypropylene (PP), and ceramic offer different levels of hydrophobicity, chemical resistance, and mechanical strength [53,54]. These properties influence not only how well the membrane can filter out organic carbon but also its longevity and maintenance requirements. In general, microfiltration represents a robust methodology for the removal of both particulate and dissolved forms of organic carbon from liquid waste streams. This is achieved through the dual mechanisms of sieving and adsorption [25,55].The presence of organic carbon in liquid waste can be detected in a number of ways, including through the use of chemical oxygen demand (COD), biological oxygen demand (BOD), total organic carbon (TOC), and dissolved organic carbon (DOC) [54]. MF metal membranes generally operated at Transmembrane Pressure(TMP) below 0,3 bar within possibility of 65–75% of TOC removal [55].

Table 2. Some of the applications of MF membrane in the removal of OC from liquid waste.

Wastewater	Membrane material	Removal rate	References
Secondary treated water	Polyolefin	25–30% in DOC	[56]
Olive oil mill	Cell body and cell holder	75.4% in TOC	[57]
Oil	Ceramic membrane	higher than 95% in TOC	[58]
Oilfield	Mixed cellulose ester (MCE)	82% in TOC	[59]
Industrial textile	Phosphate/kaolinite	69.39% in TOC	[60]
Oily	Ceramic (Al_2O_3)	96.6–97.7% in TOC	[61]
Domestic	Membrane tank	65,8% in TOC and 60% in DOC	[62]

Reclamation/reuse	Polyolefin	25–30%; 20–25% of COD	[56]
Reclamation/reuse	GAC	53% of COD	[56]
Secondary effluent	PP fibers	78% of COD	[57]
Activated sludge	Polyethersulfone(PS)	96.3% of TCOD	[63]
Poultry Slaughterhouse	PVDF	26.5% of COD	[16]

2.2. Removal Efficiency of OC from Liquid Waste by Using UF Membranes

In the implementation of UF membranes for the removal of OC from liquid waste, pore sizes are typically observed to range from 1 to 100 nanometers(nm) [13,67]. As water permeates through the porous structure of the membrane, larger organic molecules such as humic substances, proteins, and colloids are retained on its surface or within its pores [52,68]. Materials like polyethersulfone (PES), polysulfone (PS), cellulose acetate (CA), and various types of modified polymer blends are commonly used due to their favorable mechanical strength, chemical resistance, and ability to form consistent pore structures [66]. In exploring the removal efficiency of OC from liquid waste using UF membranes, several case studies and practical applications underscore the versatility and efficiency of this technology [67].By integrating UF membranes into their treatment processes, many municipalities have achieved substantial reductions in OC levels, thereby enhancing the overall quality of discharged effluent [68]. Additionally, pilot projects in agricultural settings demonstrated its potential to manage runoff containing pesticides and fertilizers [69]. These projects have shown promising results in reducing organic load before water is released back into natural waterways or reused for irrigation purposes [73,74]

Table 3. Some of the applications of UF membrane in the removal of OC from liquid waste.

Wastewater	Membrane material	Removal rate	References
Oil and grease	PS and a polyacrylonitrile (PAN)	96.3% in TOC	[72]
Oily	PS	99.7% in TOC	[73]
Municipal	Stainless steel	up to 50% in terms of COD and TOC	[74]
Oily	PVDF	98% in TOC	[75]
Oily	PS	93,5% in TOC	[73]
Vegetable oil	PS	87% in TOC	[76]
Poultry Slaughterhouse	PES	8.8% of COD	[16]
Influent from the treatment plant	PVDF	78% of COD and 91% of BOD_5	[77]
Pig manure	PVDF	Total COD mg/L= 15000	[78]
Sieved and settled manure supernatant (SAS)	PVDF	Total COD mg/L= 20000	[78]
Sieved, biologically treated and SBS	PVDF	Total COD mg/L= 160	[78]
Biologically treated wastewater	Zirconium oxide	52% of COD; 45% of BOD	[79]
Vegetable oil	PS	91% in COD; 87% in TOC	[80]
Urban	Zirconia (ZrO_2) and Al_2O_3	97% of COD	[81]
Anaerobically digested sludge	PES	(66% COD removal	[82]
Raw sewage ween	PVDF	138±26mg/L of COD	[83]
Primary clarifier effluent	PVDF	78±30 mg/L of COD	[83]

Urban	Polyolephine	43mg O_2/L 0f COD and 17mg O2/L of BOD_5	[84]

2.3. Removal Efficiency of Phosphorus Compounds from Liquid Waste by Using MF Membrane

For effective removal of phosphorus compounds from liquid waste, MF has emerged as a promising alternative [87,88]. Combined with other methods such as biological treatment or chemical precipitation, it serves as an excellent pre-treatment step [89,90]. The MF membranes facilitate the concentration of phosphorus compounds by filtering out larger solids and colloidal particles that might otherwise interfere with subsequent treatment stages [89]. The practical implementation of MF membranes for the removal of phosphorus compounds from liquid waste has seen considerably success across various wastewater (Table 4). By using a series of membrane modules with pore sizes optimized for capturing fine particulate matter and colloidal phosphorus, the facility achieved a reduction in total phosphorus levels to below 0.1 mg/L, significantly surpassing local environmental standards [90]. However, when combined with coagulation or adsorption, the efficiency can be increased to 80-95% [93,94]. PO_4^{3-} removal rates can reach up to 11% for MF alone, 91% for MF-NF and 99.7% for MF softening [87].

Table 4. Some of the applications of MF membrane in the removal of phosphorus compounds from liquid waste.

Wastewater	Membrane material	Removal rate	References
Secondary treated water	Polyolefin	5–8% of TP	[56]
Reclamation/reuse	Polyolefin	5–8% of TP	[56]
Reclamation/reuse	GAC	13% of TP	[56]
Sedimentation pond	PP fibers	7% of TP	[57]
Activated sludge floc	PS	82.6 % of TP and 70.8 % of PO_4^{3-}	[63]
From Automobile plant	Al_2O_3 ceramic	99.7% of PO_4^{3-}	[93]
Phosphoric acid	Carbon	55.3% in acid form	[94]
Liquid crystal display	MCE	99% of PO_4^{3-}	[95]
Poultry Slaughterhouse	PVDF	5.6% of TP	[16]
Urban wastewater tertiary	Propylene	7,6mg/L in TP and 5,9mg/L of PO_4^{3-}	[84]

2.4. Removal Efficiency of Phosphorus Compounds from Liquid Waste by Using UF Membrane

UF represents a highly versatile and advanced method for the removal of contaminants from liquid waste, including phosphorus compounds [96]. The fundamental principle underlying this method is size exclusion, whereby the membrane's pore size functions as a physical barrier. This obstruction facilitates the selective permeation of water and smaller molecules while retaining larger phosphorus-containing particles [97]. This approach is particularly effective for particulate phosphorus and larger colloidal forms. The material composition and surface characteristics of the membrane are also of great consequence in this regard [98]. Membranes with charged or hydrophilic surfaces have the potential to enhance adsorption efficiency by attracting oppositely charged phosphate ions or other phosphorus species (Table 5). Due to its smaller pore size, UF offers better removal of phosphorus compounds (50-80%) [91]. When combined with coagulation, removal efficiencies of 90-99% can be achieved [99]. UF effectively separates phosphorus compounds by size exclusion mechanisms without the need for additional chemicals, thus minimizing secondary pollution concerns [100].

Table 5. Some of the applications of UF membrane in the removal of phosphorus compounds from liquid waste.

Wastewater	Membrane material	Removal rate	References
Car wash	Zirconia Oxide	Phosphorus (100%) with $FeCl_3$ coagulant	[101]
Aqueous solution	Iron oxide/hydroxide	93.6% of PO_4^{3-}	[102]
Municipal	Anthracite	>96% in TP	[103]
Poultry Slaughterhouse	PES	16.7% in TP	[16]
Forms micelles	Acrylonitrile	> 91% of PO_4^{3-}	[104]
From the treatment plant	PVDF	85% in TP	[77]
Pig manure	PVDF	Pt mg/L= 80	[78]
Sieved and settled manure	PVDF	Pt mg/L= 150	[78]
Sieved and biologically treated	PVDF	TP mg/L=30	[78]
Biologically treated	Zirconium oxide	25% of TP	[79]
Biologically treated	Zirconium oxide	55% of Pt	[79]
Vegetable oil	PS	85% of PO_4^{3-}	[76]
Municipal: raw sewage weens	PVDF	4,4±0,6 mg/L in TP and 4±0,8 mg/L of PO_4^{3-}	[83]
Municipal: primary clarifier effluent	PVDF	4,1±1 mg/L in TP and 3,4±1,6 mg/L of PO_4^{3-}	[83]
Urban	Polyolephine	4 mg/L of PO_4^{3-}	[84]

2.5. Separation Efficiency of Nitrogen Compounds from Liquid Waste by Using MF Membrane

Nitrogen compounds are ubiquitous in agricultural runoff, wastewater treatment plants, industrial effluents, and household waste, posing significant environmental challenges [105]. These compounds primarily include ammonia (NH_3), nitrates (NO_3^-), nitrites (NO_2^-), and total kjeldah nitrogen (TKN) [107,108]. The separation of them from liquid waste using MF membranes is generally less effective when these membranes are used alone [109,110]. Nevertheless, when used in combination with other treatment processes, MF can contribute to nitrogen removal efficiencies [109]. The performances of MF for nitrogen compounds removal are given in Table 6.

Table 6. Some applications of MF membrane in removal of nitrogen compounds from liquid waste.

Wastewater	Membrane material	Removal rate	References
Secondary treated	Polyolefin	5–10% of TN	[56]
Reclamation/reuse	Polyolefin	5–10% of TN	[56]
Secondary effluent discharged	PP fibers	40 percent of TKN	[57]
Activated sludge floc	PS	68.1 % of TN; 95.3 % in NH_4^+ and 9.7% of NO_3^-	[63]
Urban	Propylene	35mg/L of TN; 25 mg/L in NH_4^+; 3,2	[84]

		mg/L of NO_3^-; 1,1mg/L of NO_2^-	

2.6. Separation Efficiency of Nitrogen Compounds from Liquid Waste by Using UF Membrane

The efficiency of UF in separating nitrogen compounds from liquid waste relays on several factors including membrane material and structure [112,113] (Table 7). Membrane materials can be organic polymers or inorganic substances tailored for specific separation needs [112]. Proper selection ensures optimal interaction between nitrogenous compounds and the membrane surface [113]. UF can contribute to nitrogen removal efficiencies of 80-95% when used in combination with other treatment processes [114]. Using UF technology, the liquid fraction of digestate pre-treated by electrocoagulation with Fe electrodes rejects 82% of NH_4^+ and 49% when using Al electrodes [115]. In their experimental work, [116] found that the nitrogen efficiency of anaerobic digestate in the agricultural sector produced by pressure-driven UF is around 75–95 % and 85–99 %.

Table 7. Some applications of microfiltration membrane in removal of nitrogen compounds from liquid waste.

Wastewater	Membrane material	Removal rate	References
Poultry Slaughterhouse	PVDF	32.1% of TN	[16]
Forms micelles	Acrylonitrile	> 86% of NH_4^+	[104]
Influent from the treatment plant	PVDF	98% of NH_4^+	[77]
Sieved and settled manure supernatant (SAS)	PVDF	TKN mg/L= 900	[78]
Biologically treated	Zirconium oxide	10% of TN	[79]
Biologically treated	Zirconium oxide	26% of TN	[79]
Urban	ZrO_2 and Al_2O_3	96.2% of (NH_4^+)	[81]
Anaerobically digested sludge	PES and one PVDF	13% of NH_4^+	[82]
Municipal: raw sewage ween	PVDF	29±3mg/L in TN and 39,4±11,6mg/L of NH_4^+	[83]
Municipal : primary clarifier effluent	PVDF	28,1±2,3 mg/L of TN	[83]
Urban tertiary	Polyolephine	38 mg/L of TN; 19 mg/L in NH_4^+; 12 mg/L of NO_3^- and 1,3mg/L of NH_2^-	[84]

3. Comparison

MF typically removes larger suspended solids, bacteria, and particulate organic matter (>0.1 µm), while UF can also retain macromolecules, colloids, and some dissolved organic compounds due to its smaller pore size (1–100 nm) [11,117]. These differences directly influence their performance in removing key pollutants such as TOC, TP, and various nitrogen species. Table 8 summarizes findings from recent studies comparing the removal efficiencies of MF and UF for OC and nutrients under various conditions and membrane configurations.

Table 8. comparison between MF and UF removal efficiency.

Membrane	Target Compounds	Removal Efficiency (%)	Main Mechanism	Advantages	Limitations
MF	TOC, TSS, some TP	60–75	Sieving	Low cost, easy operation	Limited nutrient removal

UF	TOC, TP, TN	75–99	Sieving + adsorption	High selectivity	Fouling, costlier

4. Conclusion

The separation efficiency of OC and nutrients was found to be low, particularly when MF and UF are applied directly without a pretreatment system. While MF and UF may not achieve high removal efficiencies for all dissolved contaminants, they are effective for particulate and colloidal matter. Moderate levels of removal were observed for higher molecular weight OC and colloidal organic matter, particulate phosphorus (PP) and particulate nitrogen. The removal of nitrogen and phosphorus in their ionic forms from liquid waste using MF and UF is somewhat more complex, as these processes are generally not effective for removing dissolved ions. The optimization of both pre-treatment and post-treatment processes is fundamental to enhance the separation efficiency of OC, phosphorus, and nitrogen compounds from liquid waste by using MF and UF membranes. The aforementioned studies confirm that OC is elevated in the instances of MF rejection, whereas inorganic elements predominantly remain in the permeate. The utilization of UF facilitates the concentration of OC, TP and TN in the concentrate, while only ionic forms may pass through the UF membrane pore.

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Abbreviations

The following symbols and abbreviations are used in this manuscript:

%	Percentage
µm	Micrometer
BOD5	Biochemical Oxygen Demand, 5 days
COD	Chemical Oxygen Demand
Da	Daltons
DOC	Dissolved Organic Carbon
h	Hour
kDa	KiloDaltons
kPa	Kilopascal
LMH	Liters per square meter per hour
m/s	Meter per second
m	Meter
m2	Square meter
MF	Microfiltration
mg/L	Milligram per Liter

min Minute
MWCO Molecular weight cut-offs
NH_4^+ Nitrogen Ammonia
nm Nanometer
NO-2 Nitrites
NO_3^- Nitrates
OC Organic Carbon
Pa Pascal
PAC Powdered activated carbon ,
PN Particulate Nitrogen
PO_4^{3-} Phosphates
POC Particulate Organic Carbon
PP Particulate Phosphorus
PVDF Polyvinylidene Fluoride ,
SS Suspended Solids
TCOD Total Chemical Oxygen Demand
TKN Total Kjeldahl Nitrogen
TMP Transmembrane Pressure
TN Total Nitrogen
TOC Total Organic Carbon
TP Total Phosphorous
TSS Total Suspended Solids
UF Ultrafiltration

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