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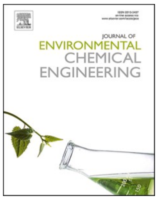

A review of membrane-based dewatering technology for the concentration of liquid foods

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ABSTRACT

The imperative to establish environmentally friendly and sustainable food processing techniques has compelled the food industry to explore alternative approaches that uphold food quality, ensure nutritional integrity, and minimize energy consumption. Extensive research conducted in the past decade has substantiated the superiority of membrane-based dewatering technology over conventional methods, owing to its ability to retain nutrients effectively while minimizing energy requirements. Notably, forward osmosis (FO) and membrane distillation (MD) have emerged as viable membrane technologies for food processing in the industry. However, recent reviews have underscored the prominence of FO in the enrichment of liquid food, positioning it as a preferred choice among other membrane-based processes. This review paper aims to elucidate the advancements and contributions of FO and MD in the realm of food processing while evaluating their maturity and technology readiness level for food concentration. Moreover, it endeavors to delineate specific parameters, including pretreatment techniques, membrane cleaning strategies, and membrane configurations/modules tailored to liquid food sources' distinct dewatering requirements. Although most FO and MD studies have focused on lab-scale fruit juice and whey concentration, future investigations should encompass pilot-scale process development alongside comprehensive techno-economic analyses to facilitate the smooth transition of these technologies to an industrial scale.

1. Introduction

Ensuring food security to meet the world's rapidly growing population is the most important global challenge. By 2050, the population is expected to reach 9 billion, leading to a projected increase in food demand from 59 % to 98 % [1]. However, water scarcity, climate change, and resource consumption for energy production pose significant obstacles to global food supply [2]. Food processing has long been employed to meet consumer demands for convenient food products and has played a vital role in economic development across societies for centuries [3]. It compasses various physical, chemical, and biological processes that alter raw agricultural ingredients into safe, flavorful, and nutritious consumable food products, enhancing their shelf life and texture [4]. Within the food processing industry, the concentration of liquid food stands out as a crucial sector, involving the removal of naturally present water from freshly squeezed juice during processing to improve storage shelf life and facilitate packaging and transportation [4–6].

The selection of food processing methods varies depending on the type and texture of the food. For instance, simply squeezing mango, apple, or pineapple fruits may not yield sufficient juice. Therefore, the food industry has made efforts to employ appropriate techniques that preserve natural nutrients, flavor, and product quality during processing and storage. Filtration serves as a prime example of physical separation methods in food processing, including conventional filtration,

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Nomenclature

AGMD	Air gap membrane distillation	MPD	m-phenylenediamine
AL	Active layer	NF	Nano filtration
CP	Concentration polarization	PA	Polyamide
DCMD	Direct contact membrane distillation	PAO	Pressure assisted osmosis
DS	Draw solution	PI	Phase inversion
ECP	External Concentration polarization	PS	polysulfone
ENM	Electrospinning nanofiber membrane	RO	Reverse osmosis
FO	Forward osmosis	RSF	Reverse solute flux
FS	Feed solution	S	Structural parameters
ICP	Internal Concentration polarization	SGMD	Sweeping gas membrane distillation
IP	Interfacial polymerization	SL	Support layer
LEP	Liquid entry level	TMC	trimesoyl chloride
MD	membrane distillation	TP	Temperature polarization
MF	Microfiltration	TRL	Technical readiness level
		UF	Ultrafiltration
		VMD	Vacuum membrane distillation

centrifugation, and mechanical expression. Other separation and concentration processes, such as crystallization, distillation, and solvent extraction, heavily rely on heat as the driving force for phase separation. These approaches enable the enrichment of liquid foods used in the industrial production of sugar, vegetable oils, and ethanol.

Although these technologies have gained widespread use in the food industry, there are concerns about sustainability due to potential environmental challenges related to storage, disposal, energy consumption, and water usage. Reports form the United States (U.S.) indicate that energy consumption in the food industry increased from 8 % in 2010 to 10 % in 2018 compared to the manufacturing sectors [7,8]. Moreover, food processing requires significant amounts of water, with the US food processing industry estimated to generate 1.4 billion liters of wastewater annually [7,9]. For example, the production of dairy products like milk and cheese consumes an average of 1.8 MJ/kg and 3.94 MJ/kg of fuel energy, as well as 255 L/kg and 3178l L/kg of water, respectively [10,11]. To address these concerns, alternative dewatering methods such as membrane technology are being proposed as a promising future solution to maintain the nutritional and sensory properties of food while minimizing pollutants discharge and energy consumption.

1.1. Application of membrane technology in food processing

In the pursuit of enhancing the energy efficiency of the dewatering process, membrane technology has emerged as a viable solution, serving as a pre-concentration step that reduces water content and minimizes thermal energy costs before evaporation [12]. A crucial advantage of membrane technology in the food industry is its ability to produce safe, high-quality, and nutritionally rich food products [13]. Furthermore, it can be seamlessly integrated with other separation processes, allowing for the development of hybrid technologies while also being more accessible and straightforward to operate compared to conventional methods [13,14]. Consequently, the food processing industry accounts for a significant portion, around 20–30 % of global membrane sales [5] with the dairy industry alone utilizing approximately 40 % of membrane technology [5]. Among the membrane-based pressure-driven processes, microfiltration (MF) and ultrafiltration (UF) are commonly employed in the food industry as pretreatment units, effectively removing unwanted macromolecules and microorganisms from raw liquid food prior to further processing [15,16]. While RO provides a lower concentration factor than evaporation, it offers distinct advantages in concentrating sugar, fruit, and vegetable juices, operating at lower temperatures, and preserving food quality [6].

Economic factors often pose significant constraints to the wider adoption of membrane technology beyond current applications. While membrane-based pressure-driven processes have lower energy requirements compared to conventional dewatering methods such as the drying process [10], their energy consumption remains relatively higher than the osmotic membrane processes like forward osmosis (FO) and membrane distillation (MD)). Consequently, FO and MD processes offer more promising prospects, high product quality, high concentration factors, low membrane fouling potential, and lower energy consumption [17]. However, the use of polymeric membranes for juice purification presents challenges when scaling up the technology, owing to low packing density and high membrane replacement costs [18,19]. Regular membrane cleaning is also necessary to maintain optimal performance, but this process can be time-consuming, and expensive and may involve chorine-containing chemicals in the solution [20]. Therefore, it is crucial for food processing and preservation methods to maintain food freshness, ensure safety and nutrient retention, and provide practical shelf life while addressing these challenges.

Among membrane technologies, FO and MD processes have gained significant interest in the concentration of liquid food due to their operation at low temperatures and pressures, along with benefits such as high product quality, high concentration factors, low membrane fouling potential, and lower energy consumption [17]. Therefore, FO and MD hold more promise for industrial food processing applications compared to other pressure-driven membrane processes and classical distillation. Bibliometric analysis using Vosviewer software (Fig. 1) provides insights into research trends related to food processing utilizing FO and MD processes. The analysis groups keywords based on research interest and categorizes them according to the average publication year, represented by a color gradient ranging from blue (older publications) to green (even distribution across the timespan) and yellow (recent publications). The analysis reveals that food processing using the FO process has gained significant attention in recent years (Fig. 1a), while the MD process has primarily been studied for fruit juice processing since 1992 (Fig. 1b). Despite several decades of study on the MD process and advancement in the FO process, limited research on liquid food concentration has been conducted at the commercialization scale.

However, there is still significant room for advancement in membrane technology within the food industry, particularly when compared to conventional methods like evaporation. The maturation of membrane processes remains a key priority, with substantial efforts dedicated to their development and improvement. These efforts are primarily aimed at achieving sustainability and economic goals, ultimately aiming to replace conventional processes in the food industry. Therefore, this review paper offers a comprehensive examination of the practical implementation of FO and MD processes, specifically focusing on the concentration of liquid foods. It delves into the challenges and influential factors that impact the performance of both processes. While previous review papers [21–23] have primarily focused on process

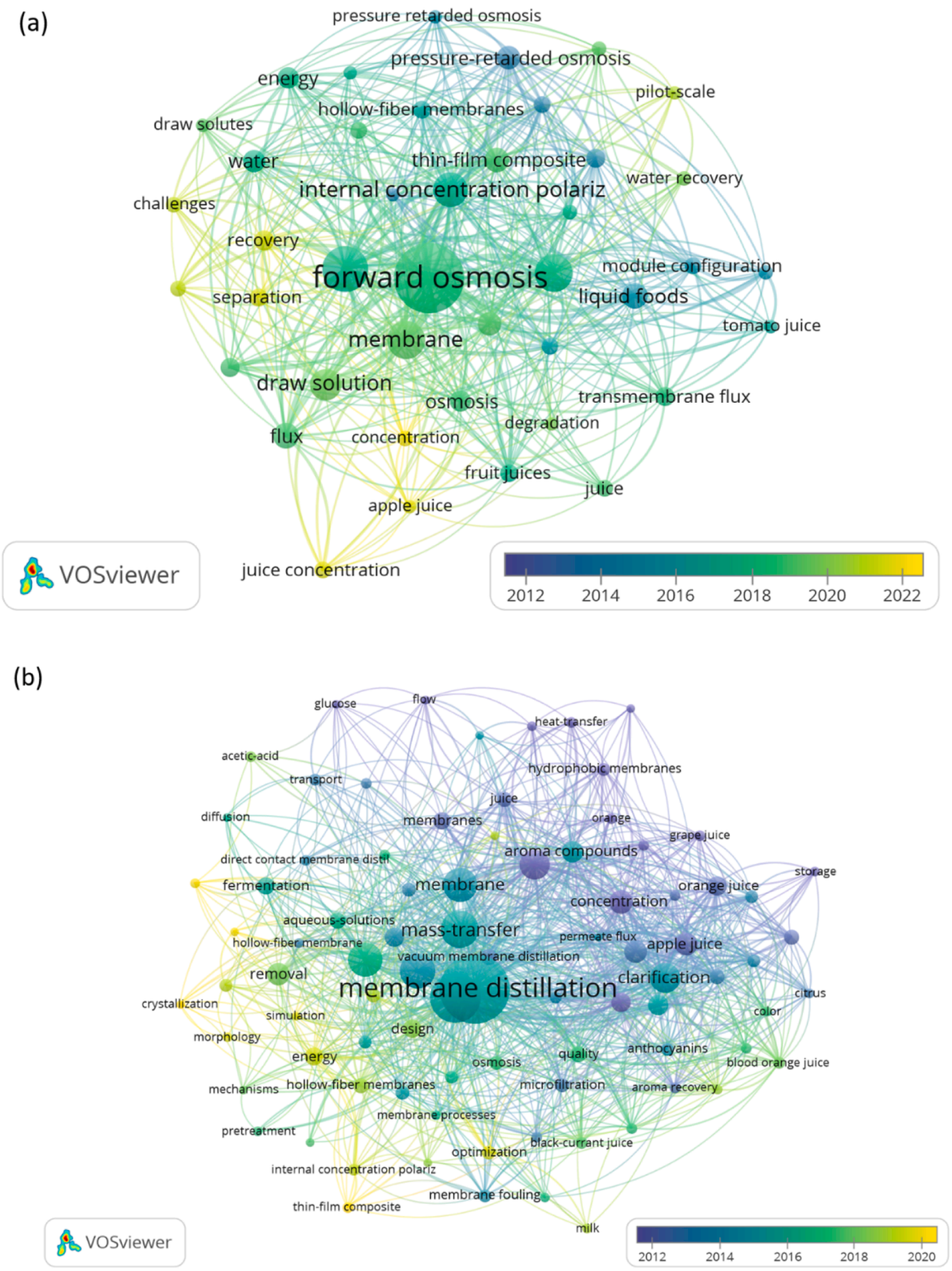

Fig. 1. The bibliometric analysis regarding research interests concerning food in core journals from the Web of Science over the last 10 years: (a) FO process and (b) MD process.
Source: Prepared by authors, using Vosviewer software.

parameters and membrane fabrication, they have not sufficiently connected these aspects to real-world applications in the food industry. In this regard, this paper provides a perspective framework that assesses the technical readiness level (TRL) of FO/MD processes for liquid food concentration, considering their potential for commercialization. Also, it highlights existing limitations and provides valuable insights to overcome these challenges. .

2. Membrane-based processes for the concentration of liquid foods

2.1. Forward osmosis (FO)

FO is a natural phenomenon involving the movement of water molecules across a semi-permeable membrane, driven by the osmotic pressure difference between bulk solutions. Unlike other processes, FO does not require external energy as a driving force. The FO system consists of a hydrophilic FO membrane, a concentrated draw solution (DS) with higher osmotic pressure, and a low feed solution (FS) concentration. The FO system can operate in either continuous flow or batch mode. In the batch-flow mode, the DS is not regenerated after dilution, making it a one-time disposable process. Conversely, in the continuous-flow FO mode, the DS is regenerated and reused, while the FS on the feed side is constantly circulated, and the diluted DS on the draw side is regenerated and recirculated [24]. An asymmetrical FO membrane consists of a support layer (SL) and an active layer (AL) or dense layer. The FO membrane can be oriented in two positions, one for FO mode with AL facing FS and the other for pressure retarded osmosis (PRO) mode with the AL facing the DS.

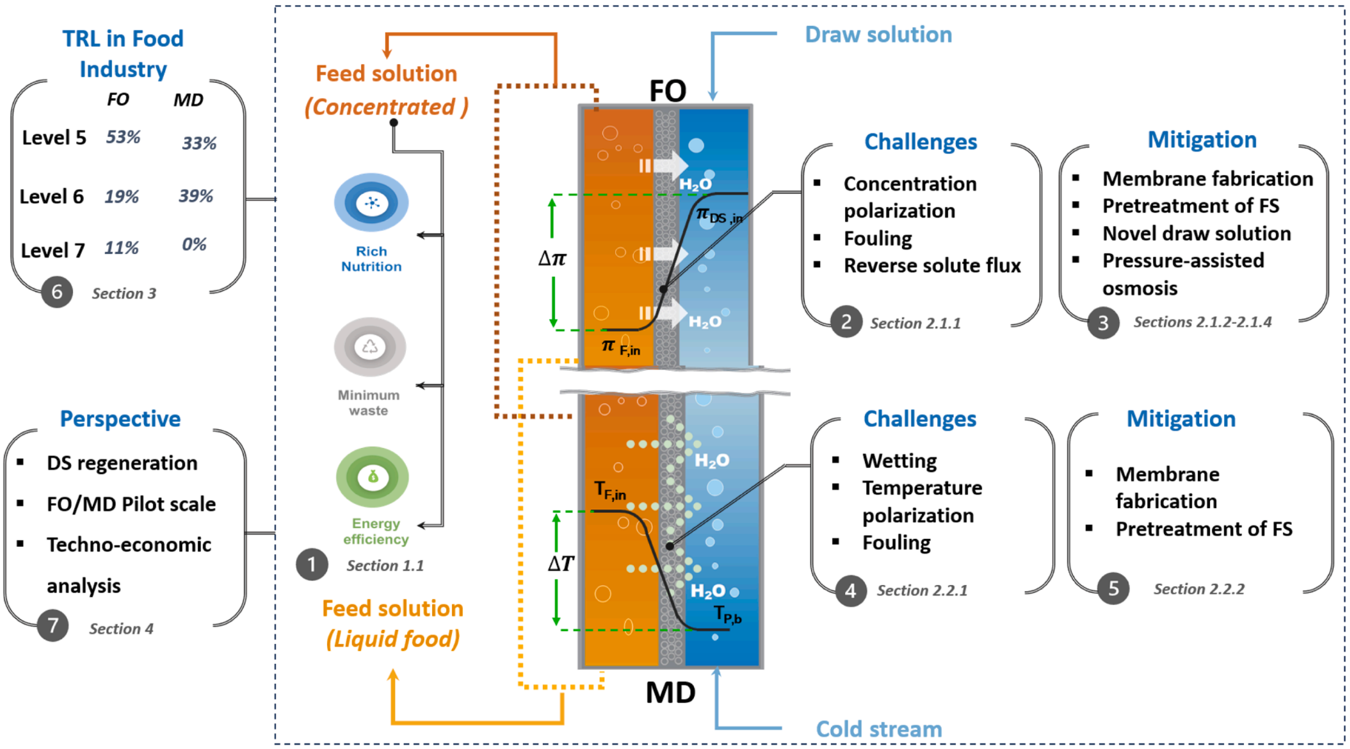

Fig. 2. Objective summary of FO vs. MD on dewatering technology for liquid food concentration.

2.1.1. *Challenges*

2.1.1.1. Concentration polarization. Concentration polarization (CP) is a significant issue that affects both sides of the membrane in FO. It occurs when solutes accumulate near or within the membrane surface, forming a boundary layer with a higher concentration than the bulk, leading to a decrease in the osmotic pressure differential, which limits the obtainable water flux. CP targets both the AL and the SL of the membrane, and it is further classified as external concentration polarization (ECP) and internal concentration polarization (ICP).

Given the inevitability of CP in the FO process, significant attention has been devoted to addressing it as a critical drawback in the concentration of liquid foods. Numerous studies have proposed various mitigation approaches to minimize the effects of CP, including membrane orientation, fabrication techniques, and mechanical methods. Most FO studies have concluded that operating in FO mode yields the best performance for liquid food concentration, as the impact of ECP is negligible [25–27]. However, these studies have often encountered challenges related to poor dewatering of liquid foods due to the influence of ICP. Improving the structural parameters (S) of the support layer (SL) of the FO membrane, which include porosity, thickness, and tortuosity, offers a potential avenue for reducing ICP. Nevertheless, there have been limited studies focused on fabricating FO membranes, especially for the food processing industry [25,26,28]. Notably, studies utilizing the electrospinning method for the fabrication of SL in FO membranes have shown improved *S* value, resulting in increased concentrations of sugarcane juice, apple juice, and whey, as discussed in detail in Section (*2.1.2.1*).

Furthermore, Chanukya et al. [29] explored the application of ultrasound to mitigate the impact of CP during the concentration of different feed model solutions containing pectin and sucrose. Their findings revealed that operating in FO mode in an ultrasonic bath at 30 kHz. Resulted in a 5 % increase in sucrose concentration. However, in the case of pectin, the formation of a gel layer on the AL surface led to severe ECP, and no improvement was observed [29]. In a subsequent study, the adverse effect of ECP was reduced by adjusting the feed flow velocity to minimize the formation of fouling layers on the membrane surface [30]. These findings indicate that dynamic flow adjustments can effectively manage ECP, making its detrimental impact on FO process performance less significant compared to ICP.

2.1.1.2. Fouling. Fouling in membrane-based processes is defined as the accumulation of foulant materials on the membrane surface, resulting in reduced membrane productivity, selectivity, and increased hydraulic resistance [31]. Fouling can manifest in different forms, including pore blockage or the formation of gel layers or cakes due to solute accumulation. While the FO process is generally less susceptible to fouling compared to pressure-driven processes, it is a significant concern in food processing, as fouling can significantly degrade FO performance. In FO mode, fouling occurs on the AL surface and is referred as external fouling. On the other hand, in the PRO mode, fouling may penetrate or accumulate on the SL and the inner sidewalls of the AL, resulting in internal fouling and potentially triggering the ICP effect.

Several studies on FO have investigated the effect of fouling on its performance in the concentration of fruit juices and dairy products [30, 32–35]. External fouling can be mitigated by implementing pretreatment methods on the feed side to remove suspended solids from the FS [36]. As a result, numerous research works have examined FO membranes to analyze and address fouling phenomena during the concentration of substances like pectin or whey, as discussed further in Section (*2.1.3*). To reduce fouling tendencies in food processing using the FO process, strategies such as pretreatment of the FS, membrane cleaning, or adjusting the cross-sectional flow velocity have been explored. Certain FO studies have investigated fouling control mechanisms when concentrating fruit juice containing pectin. They have observed that employing pretreatment methods such as centrifugation, sedimentation, UF, or MF, along with physical membrane cleaning, has contributed to maintaining flux recovery.

2.1.1.3. Reverse solute flux. Reverse salt flux (RSF) is an inherent challenge in the FO process, wherein the DS diffuses through the membrane into the FS. The severity of RSF increases with higher DS concentrations and smaller DS ion radii [37,38]. Maintaining product quality is an essential criterion for separation and concentration methods in the food industry. RSF poses a significant challenge to the commercialization of FO for liquid food concentration. Recent FO studies have explored and evaluated novel DS options for food processing. These studies demonstrated that novel DSs, such as food preservatives, additives, and glucose salts, can help mitigate the RSF effect [28,39–42], as discussed in detail in Section (*2.1.2.2*). Additionally, these studies suggested replacing sodium chloride (NaCl) with a novel DS when concentrating dairy products and fruit juices to minimize RSF and preserve food product quality. Other investigations have focused on FO membrane materials and improvements to the SL to reduce the RSF effect and obtain high-quality apple juice or whey products [25,28]. Moreover, pressure-assisted forward osmosis (PAFO) has been studied to minimize further diffusion of solutes from the draw side to the feed side, as detailed in Section (2.1.4).

2.1.2. FO process parameters

2.1.2.1. FO membranes. FO membranes play a vital role in the separation and feasibility of GO systems in the food industry. High wettability characteristics, high salt rejection, and anti-fouling potential maximize the dewatering rate. During the concentration of liquid food by the FO process, the transmembrane flux of the FO membrane is affected by three main factors: type, module, and orientation of the membrane. The type of manufacturing material and the fabrication method results in different types of FO membranes, and the most adopted in FO applications are cellulose triacetate (CTA) and thin-film composite (TFC). The FO membrane has four different membrane modules, such as plate-and-frame, spiral-wound, tubular, and hollow fiber [43].

Previous studies have examined both RO and FO membranes for the concentration of liquid food using the FO process [33,44,45]. Castello et al. [44] found that CA FO membranes achieved approximately threefold enrichment of sucrose, surprising the performance of aromatic

Table 1

Summary of FO process parameters for the concentration of liquid foods for 2009–2022.

Feed solution			Draw solution			Membrane		Time (h)	Results			Ref.
Source	*Brix°*	*Q (LPM)*	*Type*	*Con. (M)*	*Q (LPM)*	*Type*	*Configuration/ orientation*		*J_w (LMH)*	*Brix °*	*CF*	
Sucrose	0.2^a	1	NaCl	4	1	CA	Flat /FO-mode		5.8		5.7	[44]
Orange juice		4	$CaCl_2$	20^c	1	CTA	Flat /FO-mode	3	13.2		2.2	[50]
Beet juice	2.3	0.1	NaCl	0.6	0.1	CTA	Flat /FO-mode	6	~1.8	52	22.6	[46]
Pineapple juice	8.0	0.1	NaCl	0.6	0.1	CTA	Flat /FO-mode	6	~1	54.6	6.8	[46]
Grape juice	4.4	0.1	NaCl	0.6	0.1	CTA	Flat /FO-mode	6	~1	54	12.3	[46]
Sugarcane juice			Sea bittern			TFC*	Flat /FO-mode	5	13		4	[26]
Tomato juice	7.6^a		Potassium gluconate	1.5		TFC	Flat /PRO-mode		2.6			[42]
Orange juice	19.3^a		Potassium gluconate	1.5		TFC	Flat /PRO-mode		1.6			[42]
Apple juice	12.4^a		Potassium gluconate	1.5		TFC	Flat /PRO-mode		1.8			[42]
Grape juice	14.8^a		Potassium gluconate	1.5		TFC	Flat /PRO-mode		1.6			[42]
Sweet lime juice	11	0.15	NaCl	6	0.15	CTA	Flat /FO-mode	20	~2	50	*4.6*	[29]
raw whey	7.2^c	5	NH_4HCO_3	2	5	CTA	Flat /FO-mode	4	4	8.2^c	1.1	[33]
Whey protein	6^b	55^d	NaCl	0.5	22^d	*TFC	Hollow Fiber/FO-mode**	9	9.4		1.5	[35]
Apple juice	10.6	0.5	Potassium sorbate	2	0.5	*TFC	Flat /FO-mode	2.5	5	45.1	4.3	[28]
Skim milk	6.4^c	46	NaCl	50^b	7.8	CTA	Spiral-wound/ FO-mode**				~2.5	[48]
Whey	5.9^c	46	NaCl	50^b	7.8	CTA	Spiral-wound/ FO-mode**				~2.5	[48]
Grapefruit juice	10.6	10.7^d	NaCl	2	10.7^d	TFC	Flat /FO-mode	20	~5	45	5	[30]
Lime Juice	3.54 ppt		NaCl	97 ppt		PA TFC	Flat /FO-mode	0.5	~0.3	8.8		[51]
Whey cheese	6.3^c	0.12^h	NaCl			CTA	Spiral-wound/ FO-mode**	1	~2		2.7	[47]
Orange juice	15	0.15	NaCl	10	0.15	*GP	Flat /FO-mode		1.1^e	26	1.7	[52]
Skim milk	8.7^c	0.2^d	NaCl		0.2^d	CTA	Flat /FO-mode		3.1	17.3^c	2	[53]
Sugarcane juice	11.4	25	NaCl	100^c	45	Aquaporin	Hollow Fiber /FO-mode	9	6.5	15.4	1.3	[49]
Watermelon juice	6.8		glycerol	70^c			Spiral-wound/ FO-mode**			64.8	9.5	[54]
Beetroot juice	5.5	0.1	NaCl	6	0.1	CTA	Flat /FO-mode	12	1.2	60	10.9	[55]
Orange juice		6.4^d	NaCl	6	6.4^d	CTA	Flat /FO-mode	10	3.5		1.1	[56]
Watermelon juice	7.7	2	NaCl	1	2	*HPA	Flat /FO-mode	10	13		4	[57]
Orange juice	10.2		Sodium lactate	7.1		CTA	Flat /FO-mode	10	9.1	22.3	2.2	[40]
Simulated whey protein	6^c		Monosodium glutamate	3		TFC	Flat /FO-mode		19.8	15^c	2.5	[65]
Grape juice	10.5	0.5	Sodium diacetate	4	0.5	*TFC	Flat /FO-mode	72	~1	54	5.1	[58]
Pectin	2^b	40	NaCl	3	40	CTA	Flat /FO-mode		~12.5			[32]
Grape juice	15	12^d	NaCl	1	12^d	CTA	Flat /FO-mode	5	19.1^e		3.7	[58]
Apple Juice		0.6	NaCl	3.6	0.6	*TFC	Flat /FO-mode	24	6.5		2.1	[25]
Whey		0.6	NaCl	3.6	0.6	*TFC	Flat /FO-mode	64	2		1.8	[25]
Apple Juice	11	53.6^d	NaCl	4	53.6^d	CTA	Flat /FO-mode	48	~4	60	5.5	[34]

LPM: L/min, LMH: L/m^2h

CA: Cellulose acetate, CTA: Cellulose triacetate, CF: Concentration factor, PA: Polyamide, GP: Geopolymer

[a]Molar concentration (mol/L), [b]Mass concentration (g/L), [c]Weight % (w/w %), [d]Velocity (cm/s), [e]Mass flux (kg/m^2h)

*Fabricated membrane, **Pilot scale

polyamide (AG) RO membranes. Similar findings were reported by Seker et al. [33], further supporting the superiority of FO membranes over RO membranes in liquid food concentration. In a recent study, a TFC-FO membrane demonstrated higher water flux compared to a CTA-FO membrane, successfully concentrating various fruit juices (tomato, orange, apple, and grape) within a pH range of pH 2–11, aligning with the pH range of typical fruit juices (4−5) [42]. Conversely, another study [34] indicated that the CTA-FO membrane exhibited better suitability for apple juice concentration compared to the TFC-FO membrane. This was attributed to the CTA-FO membrane's superior membrane flux stability and lower RSF effect during the FO process. The concave-convex surface morphology of the TFC-FO membrane resulted in increased surface roughness and fouling tendencies, contrasting with the CTA-FO membrane.

Most studies on the concentration of liquid foods using FO utilized commercially available CTA-FO membranes (Table 1) due to their well-established and commercialized nature. However, recent efforts have focused on developing TFC-FO membranes specifically for food processing applications [25,26,28,34,35]. For example, studies have evaluated the performance fabricated through conventional phase inversion (PI) and interfacial polymerization (IP) methods for fruit juice processing [26,28,41]. Mondal et al. [26] employed polysulfone (PS) as the substrate material for the support layer (SL) and polyamide layer (PA) composed of m-phenylenediamine (MPD) (3 % w/v in H2O) and trimesoyl chloride (TMC) (0.12 % in Hexane) to successfully concentrate sugarcane juice up to 4 times after 5 h of FO operation. Similarly, Zhang et al. [41] fabricated a TFC-FO membrane by modifying the PA layer (4 % MPD and 0.15 % TMC) coated on the substrate material (PSF) to improve solute rejection and obtain higher water recovery from grape juice. The results demonstrated the stability of the fabricated FO membrane during long-term operation (72 h) for grape juice concentration (54 Brix°).

In recent studies on FO membrane fabrication for fruit juice processing, the electrospinning method has been employed to enhance the characteristics of the SL in the TFC-FO membrane. One such study developed a TFC-FO membrane by fabricating a PSF-based electrospun nanofiber (EN) SL coated with a PA layer to concentrate various liquid food sources [25]. The results revealed that the EN PSU-based SL of the FO membrane exhibited minimal ICP effects compared to conventional FO membranes, primarily due to its high porosity of 83 %. Furthermore, the nanofiber TFC membrane successfully achieved the dewatering of whey, mango juice, and apple juice with concentration factors of 1.8, 2.5, and 2.1, respectively [25].

Membrane orientation is another factor affecting the transmembrane flux in the FO process. Studies by Nayak et al. [46] and Zhang et al. [41] demonstrated that operating in FO mode yielded better overall performance in terms of dewatering flux and concentration factor for fruit juices compared to PRO mode. This difference was attributed to more severe membrane fouling and the increased impact of the concentrative ECP effect in the PRO mode. Conversely, Long et al. [42] and An et al. [28] found that the average water flux values were nearly identical between the two modes during apple juice concentration using the FO process. Their findings were attributed to the comparable effects of membrane fouling in the PRO mode and dilutive ICP in the FO on water flux. However, most studies (Table 1) on liquid food concentration using FO have primarily operated in the FO mode to minimize the fouling rate and enhance FO membrane durability.

Table 1 indicates that the majority of FO studies focusing on liquid food concentration have been conducted at the lab scale using plate-and-frame FO membranes. Only three studies were carried out at the pilot scale, with two evaluating milk and whey concentration using a commercial spiral-wound CTA FO membrane [47,48]. The third study employed a commercial TFC-aquaporin hollow fiber FO membrane for sugarcane juice concentration [49]. Additionally, the fabricated FO membranes exhibited superior properties compared to the commercial ones, leading to improved FO process performance for food processing. However, the development of FO membranes specifically for liquid food concentration by the FO process has been limited, as many studies gave relied on commercially available membranes.

2.1.2.2. Draw solution (DS). The selection of a suitable DS is an essential parameter that affects separation performance in the FO process but faces challenges related to solute leakage into the FS. The ideal DS should possess characteristics such as high osmotic pressure and water solubility, lower viscosity and molecular weight, and relatively large ionic radii to minimize RSF tendency [21]. In the food industry, DS selection is also influenced by considerations of food safety, taste, smell qualities, and nutritional value of the final products. To address these concerns, various studies have been conducted to identify DS options with a reduced tendency to diffuse back to the FS side. Long et al. [46] recently investigated non-toxic gluconate salts as an alternative to inorganic DS (e.g., sodium chloride (NaCl), magnesium chloride ($MgCl_2$)) for the concentration of apple juice in the FO process. The results revealed that potassium gluconate exhibited higher water flux and significantly lower RSF compared to other gluconate salts and NaCl. Another study [39] evaluated the effectiveness of food additives as DSs in the FO process for whey concentration, and monosodium glutamate (MSG) demonstrated the highest concentration of solid content among the three food additives. Similarly, Hu et al. explored food preservatives as novel DS options for grapefruit juice concentration [41]. Among the food preservatives tested, sodium diacetate (SDA) exhibited the lowest RSF effect and successfully concentrated grape juice up to 54 Brix° after the long-term operation (72 h) of the FO process. Wang et al. [34] further confirmed the suitability of organic DSs for fruit juice concentration, highlighting the stable dewatering flux achieved with glucose and minimum back solute diffusion towards the FS side. The larger molecule size of glucose compared to NaCl and $MgCl_2$ significantly limited the RSF effect.

The influence of DS concentration on the driving force of the FO process for the concentration of liquid food was examined. Several FO studies [34,39] confirmed that increasing DS concentration enhances the dewatering rate of liquid food over time. However, other studies [32,50] reported that dewatering flux values decrease when DS concentration exceeds certain levels. This suggests that exceeding the critical DS concentration level can amplify the effects of ICP and RSF, leading to a weakened osmotic pressure difference across the membrane and reduced flux. In light of these findings, Yang et al. [39] proposed that the optimal DS concentration should be determined based on the amount necessary for liquid food concentration rather than water reclamation.

The recovery of DS poses a challenge in implementing the FO process in the food industry. Unlike other membrane processes, DS recovery is an essential step in the FO process, involving the reconcentration of diluted DS for reuse. However, limited studies have evaluated the performance of DS recovery in the FO process for liquid food concentration. For example, Long et al. [42] utilized the nanofiltration (NF) process to reconcentrate diluted potassium gluconate DS, requiring an energy-intensive operation at an external pressure of over 10 bar to achieve the desired concentration. On the other hand, a recent study [28] demonstrated the feasibility of continuous DS recovery through an integrated FO-MD system. This system operated at a constant temperature (25 ± 1 °C) for apple juice and potassium sorbate DS, while the temperature of the MD distillate was maintained at 20 ± 1 °C. This approach highlights the potential of MD as a cost-effective alternative for DS regeneration in the food industry.

DS concentration is an important parameter that influences the driving force in the FO process. FO studies have investigated DS concentrations ranging from 1 to 10 M (Table 1), which are suitable for the concentration of dairy products or fruit juice. Additionally, current studies actively explore and evaluate novel DS options, such as food additives and preservatives, demonstrating their effectiveness in overcoming the RSF effect and maintaining high-quality products compared to inorganic DS. Despite these advancements, NaCl is still used as DS in the FO process for liquid food concentration, as indicated in Table 1. However, the recovery and regeneration of DS are essential factors for industrialization and commercialization. Currently, only a limited number of studies have applied techniques such as DCMD [27,28] and NF[42] for the recovery of potassium sorbate and potassium gluconate DS, respectively. Further research and development in DS recovery methods are needed to facilitate the scaling up and widespread adoption of the FO process in the food industry.

2.1.3. Membrane fouling mitigation

To mitigate membrane fouling in the FO process for liquid food concentration, various approaches have been investigated. Pectin, a polysaccharide found in the cell wall of fruit cells, is a significant fouling agent in fruit juice concentration [31]. Depectinization, which involves enzymatic treatment of the fruit juice prior to the FO process [34], is one method to minimize fouling in the fruit juice industry. Mohanty et al. [49] found that washing the membrane surface with sodium hydroxide (NaOH) solution was more effective than DI water and osmotic backwashing in removing organic foulants from sugarcane juice. On the other hand, Li et al. [34] studied the impact of pectin fouling on the FO process performance in apple juice. They observed a significant decrease in water flux due to the formation of a thick gel fouling layer, as shown in Fig. 3c. They found that hydraulic flushing outperformed chemical washing (NaOH and sodium dodecyl sulfate (SDS)) in terms of reducing residual total organic carbon (TOC) on the membrane surface and increasing % water flux recovery, as shown in Fig. 3d-f. The effectiveness of hydraulic flushing was attributed to its ability to remove the fouling layer. The choice of membrane material also plays a role in fouling phenomena. Cleaning the CTA-FO membrane surface with NaOH may lead to TOC degradation. Therefore, Li et al. proposed hydraulic flushing as a suitable membrane cleaning method for apple juice concentration, taking into account the impact on membrane performance [34].

A recent study [30] demonstrated that hydraulic flushing, achieved by increasing the cross-flow rate of the FS, effectively prevented foulant

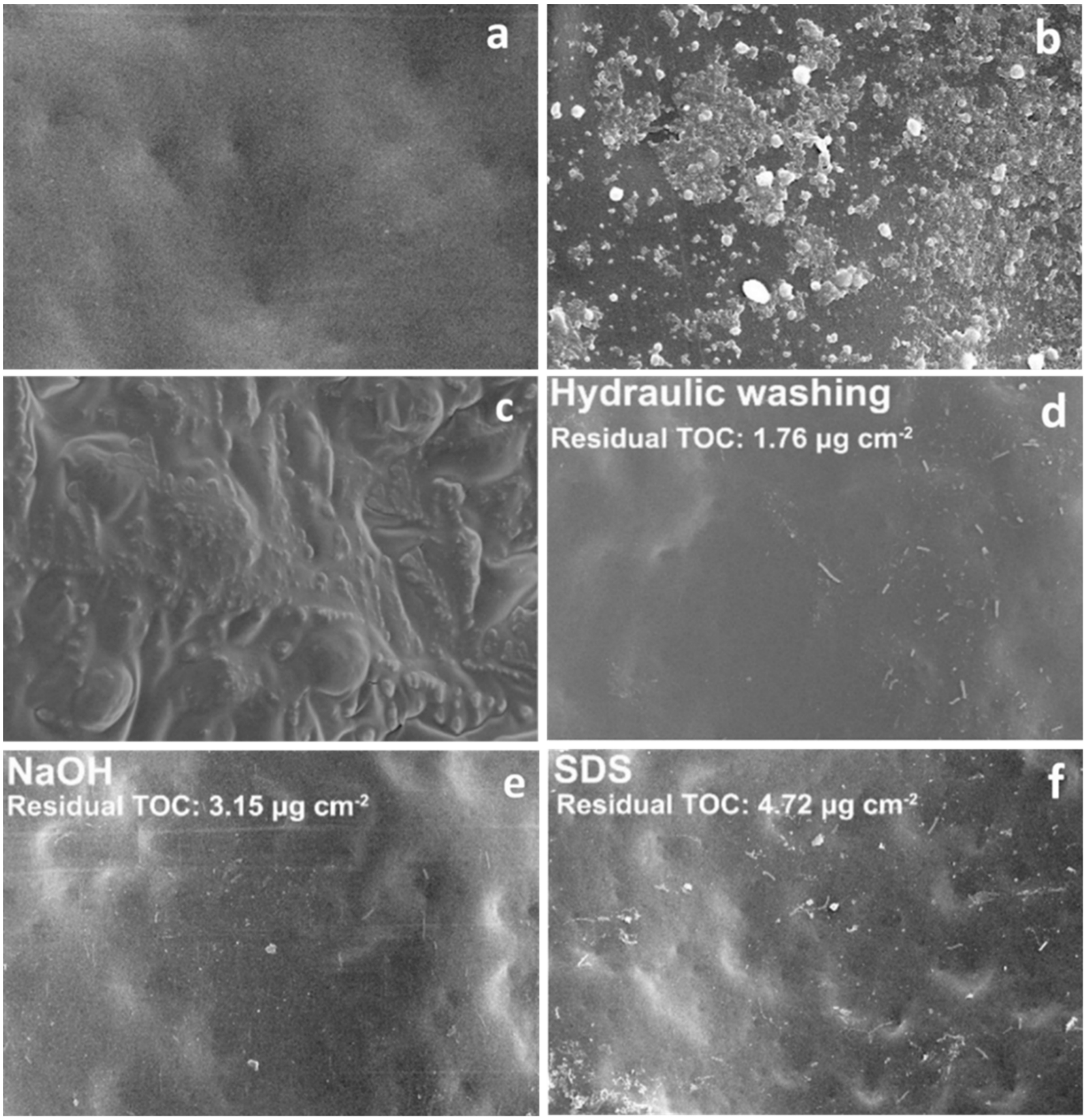

Fig. 3. SEM image of the AL of CTA-FO membrane surface of apple juice concentration after 48 h. (a) Pristine membrane, (b) fouled membrane using apple juice without pectin as FS, (c) fouled membrane using apple juice with pectin as FS, and SEM image of AL of CTA-FO membrane after cleaning for the concentration of apple juice without pectin after 10 h: (d) Cleaned by hydraulic flushing, (e) cleaned by NaOH, and (f) cleaned by SDS [34].

adhesion to the membrane by generating increased shear force. Additionally, Hong's research group [30] suggested pretreating the FS through sedimentation or centrifugation to remove bulky particles, which could be reintroduced into the juice after dewatering to prevent loss of nutritional value. They also investigated the long-term operation of FO for grapefruit juice dewatering and found that centrifuged juice and physical cleaning methods could recover the dewatering rate after each cycle.

These studies concluded that pretreatment is the best effective method for mitigating membrane fouling, and the choice of the pretreatment method depends on the characteristics of the feed solution. In terms of membrane cleaning, treating the FS prior to the FO process reduces the likelihood of fouling. Therefore, FO studies showed that physical cleaning methods are practical for recovering membrane flux after liquid food processing with FO membranes.

2.1.4. Pressure-assisted osmosis (PAO)

Current FO studies have explored the use of pressure-assisted osmosis (PAO) to enhance the concentration of liquid food through the FO process. The PAO-FO (Fig. 4) process offers advantages over traditional FO, as it reduces RSF and achieves food enrichment in a shorter operating time. Kim et al. [30] found that applying pressures ranging from 0 to 6 bar on the FS side resulted in similar dewatering rates but significantly decreased specific reverse solute flux. This indicates that PAO effectively limits the back diffusion of solutes from the draw side to the feed side. Additionally, Kentish et al. [48] and Yang et al. [39] observed that increasing the pressure on the FS side improved the dewatering flux and the quality of the skim milk and whey products, respectively. While these studies demonstrate the efficiency of the PAO-FO process compared to traditional FO, it's worth noting that the high applied pressure range (0–10 bar) is similar to that used in UF processes. Therefore, further optimization of the pressure range in PAO-FO for food processing is necessary to maximize its potential.

2.2. Membrane distillation (MD)

Membrane distillation (MD) is a thermal membrane process that enables the passage of water vapor molecules through a microporous hydrophobic membrane [59]. The driving force behind MD is the partial pressure difference created by the temperature difference on either side of the membrane surfaces. MD can be implemented in various configurations, including direct contact membrane distillation (DCMD), vacuum membrane distillation (VMD), air-gap membrane distillation (AGMD), and sweep gas membrane distillation (SGMD). Among these configurations, DCMD is primarily utilized in food processing due to its basic and straightforward (Table 2), where the heated feed (liquid) and the cool permeate (liquid) come into contact with the porous hydrophobic membrane.

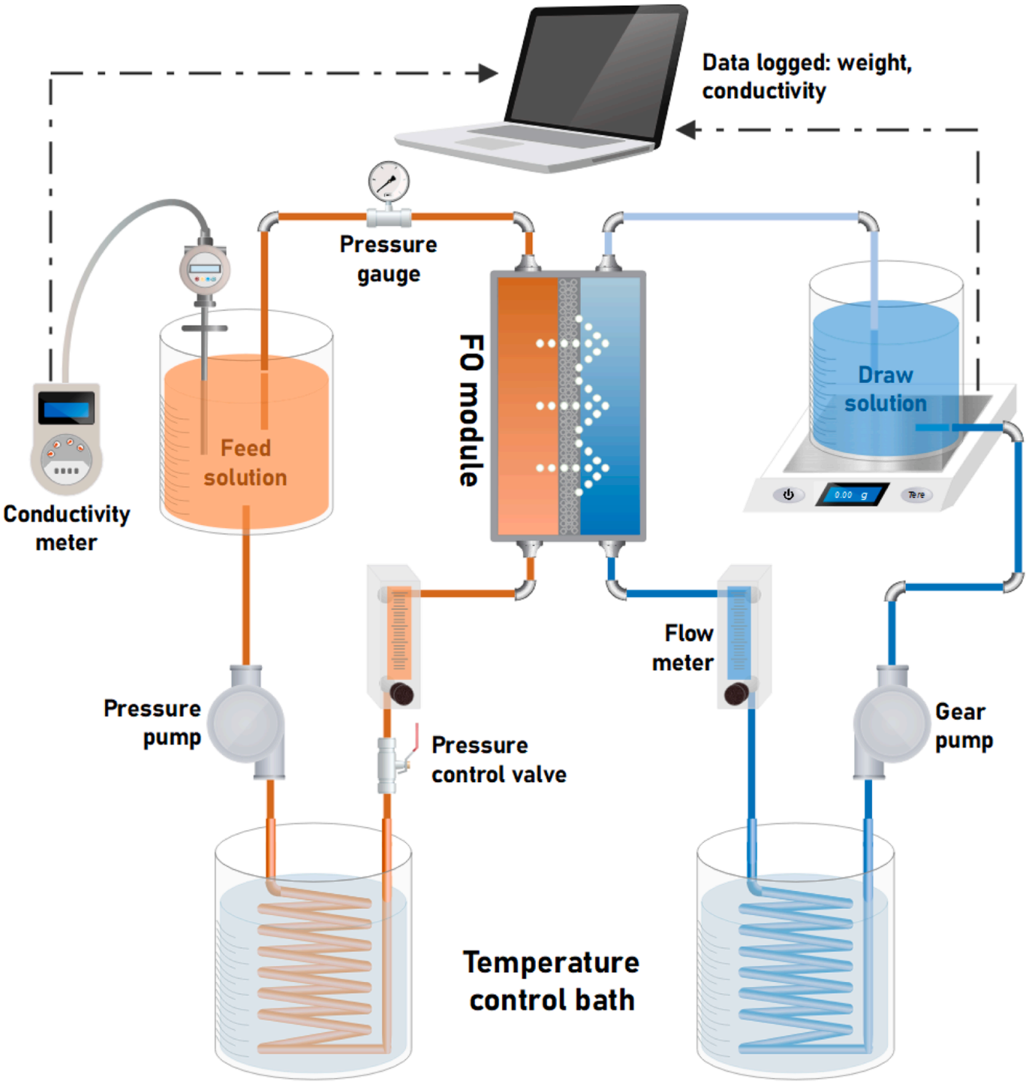

Fig. 4. Application of pressure-assisted osmosis (PAO) with the FO process for the concentration of liquid foods, adopted from [39].

Table 2
Summary of the MD process parameters for the concentration of liquid foods.

Membrane			Feed solution				Permeate side		Time (h)	Results			Ref
Configuration	*Material*	*Module*	*Source*	*Brix°*	T_h (°C)	*Q (LPM)*	T_C (°C)	*Q (LPM)*		J_w (LMH)	*Brix °*	*CF*	
DCMD	PP	Hollow fiber	Orange juice	10	40		20			5	30		[65]
VMD	PTFE		Black currant juice	12	10	6.7						21–23	[74]
DCMD	PP	Hollow fiber	Orange juice	11	34		23		20	3	~58		[77]
DCMD	VDF-TFE	Flat	Apple juice	11	60	0.8[a]	20	0.8[a]		~15	25		[76]
DCMD	VDF	Flat	Apple juice	11.4	70	0.1	20	0.1		3	65		[78]
DCMD	PP	Hollow fiber	Blackcurrant juice	22	30	0.1[a]	11	~0.2[a]	15		58.2		[79]
VMD	PTFE	Flat	Black currant juice	12	30	6.7				20.7		16.7–15.5	[75]
SGMD	PTFE	Flat	Berry fruit juice	12	45	6.7		33.3		4.9		12.1–10.3	[75]
Submerged DCMD	PP	Hollow fiber	Apple juice		30		14	0.18	2		35		[64]
VMD	PP	Flat	Date juice	18	28	0.5			~6		70		[72]
Submerged VMD	PP	Hollow fiber	Raw Sugarcane juice	50	70				15		64.8		[73]

[a] velocity
PTFE: Polytetrafluoroethylene, PP: Polypropylene, VDF: Vinylidene fluoride, TFE: Tetrafluoroethylen

2.2.1. *Challenges*

2.2.1.1. Membrane wetting. Although MD membranes offer superior selectivity compared to other membrane processes, their industrial application is limited due to wetting issues. MD relies on the transfer of gaseous mass through membrane pores, and wetting these pores lenders the process inoperable [60]. Wetting is influenced by factors such as the composition and ionic strength of the feed solution (FS), as well as membrane fouling and scaling, which exacerbate wetting [61]. Recent studies have focused on developing superhydrophobic membranes to minimize wetting [62,63]. However, only two studies have specifically addressed membrane fabrication to mitigate wetting and improve the concentration of liquid foods using the MD process. In a recent study [28], MD membranes with improved hydrophobic properties and stability were fabricated using the electrospinning method. Other studies examined the impact of fouling phenomena, implemented pretreatment methods as fouling control strategies, and minimized membrane wettability [64,65], as detailed in Sections (2.2.2.1 and 2.2.2.2).

2.2.1.2. Temperature polarization. Temperature polarization (TP) is an unavoidable phenomenon in MD systems, resulting from the temperature difference between the bulk FS and the water-membrane interface due to water evaporation and latent heat consumption. TP forms a thermal boundary layer on the membrane surface, diminishing the temperature gradient and reducing transmembrane flux [66,67]. It also limits vapor transport through the membrane, leading to decreased water recovery rates [68,69]. The impact of TP becomes more pronounced at higher temperatures of the bulk FS. Various studies have been conducted to investigate TP phenomena and explore approaches to minimize its effect in the MD process. The use of feed spacers has been shown to help maintain a temperature gradient across the membrane and minimize TP. Recent MD studies have also explored spacer designs, including 3D-printed spacers, to enhance heat transfer and mitigate the effects of TP [70,71]. However, limited efforts have been made to address TP and enhance MD performance, specifically in the context of liquid food concentration, as discussed in sections (2.2.4.1 and 2.2.4.2).

2.2.2. *MD process parameters*

2.2.2.1. MD membrane. Hydrophobicity is a key requirement for MD membranes, necessitating the use of hydrophobic materials. The membrane's hydrophobicity is determined by factors such as liquid entry pressure (LEP), thickness, pore size, pore distribution, and porosity. MD systems employ various membrane materials and module configurations, including flat sheet, spiral-wound, tubular, and hollow fiber. Most MD membranes are composed of polymeric materials with low surface energy, such as Polyvinylidene fluoride (PVDF), propylene (PP), and polytetrafluoroethylene (PTEF).

The productivity of the MD process for liquid food concentration was investigated by optimizing membrane properties, module design, and operating conditions to minimize the TP effect and membrane fouling [72]. Hollow fiber membrane modules were commonly used in MD studies for liquid food concentration, as shown in Table 2. A recent study conducted by Julian and colleagues [64] explored the use of a submerged commercial hydrophobic PP hollow fiber membrane for apple juice concentration. This study successfully concentrated apple juice up to 2-fold with minimal nutrient loss. However, it was observed that the hydrophobicity of the PP hollow fiber membrane decreased by 14 % due to the formation of a fouling layer that covered the MD membrane's pores.

Other studies focused on using fabricated MD membranes to minimize membrane wetting during FO processing. Wang et al. [27] and Liu et al. [28] utilized fabricated MD membranes as the DS recovery unit in the FO process for liquid food concentration. Wang's team [27] synthesized a conventional PTFE hollow MD membrane, while Liu et al. [28] fabricated a flat sheet PVDF-HEP electrospun nanofiber membrane (ENM) using an electrospinning method. The results demonstrated improved anti-wetting properties and thermal stability of the PVDF-HFP ENM MD membrane. It maintained a consistent dewatering rate even with a minimal temperature difference of 10 °C and various concentrations (1–1.5 M), making it suitable for re-concentrating DS in the FO process for apple juice concentration.

Table 2 reveals that approximately half of the studies focused on utilizing PP hollow fiber MD membranes for fruit juices and fragment concentration, indicating the maturity of the MD process for food processing. Among these studies, the DCMD configuration was predominantly used. However, it is worth noting that the development of MD membranes specifically tailored to address wetting and temperature polarization issues in liquid food concentration has been limited thus far, with most studies relying on commercial MD membranes.

2.2.2.2. Feed solution (FS). The FS plays a critical role in influencing the performance of the MD process. The temperature difference between the FS and the permeate side creates a partial pressure gradient and facilitates permeate flux across the MD membrane. Therefore, it is essential to determine the maximum allowable temperature on the hot side and the minimum temperature on the cold side [73]. Additionally, the composition and ionic strength of the FS can impact membrane fouling and wetting properties. However, only a limited number of studies investigated the influence of FS components on the concentration of liquid foods in the MD process.

The impact of FS temperature on the MD process was investigated in previous studies. Calabro and Drioli [65] observed that increasing the feed juice temperature in the DCMD process while keeping the coolant temperature constant at 20 °C improved permeate flux due to a higher vapor pressure gradient between the feed and permeate sides. In another study by Jonsson et al. [74], the VMD process was explored for aroma recovery from temperature-sensitive blackcurrant juice. It was found that the highest concentration factor of volatile aroma esters and lower permeate flux were obtained at a low feed juice temperature of 10 °C, demonstrating the effectiveness of VMD for gentle aroma recovery. Crisuoli and Drioli [72] demonstrated the application of VMD for concentrating date juice, achieving a concentration of 70 Brix° at a low FS temperature of 28 °C. Additionally, Jonsson et al. studied the SGMD process for aroma compound recovery from black currant and berry fruit juices [75], and their results aligned with previous findings [65], showing that the highest permeate flux and concentration factors of aroma compounds were obtained at the highest FS temperature of 45 °C.

The effect of FS concentration and source on the MD process performance was investigated. It was observed that increasing feed juice concentrations led to a decrease in permeate flux due to the high viscosity of fruit juice, which hinders transport at the MD membrane interface [65]. This study also linked flux decay to membrane fouling during the concentration of untreated orange juice. To address this issue, the same research group employed UF as a pretreatment method, resulting in an improved dewatering rate and concentration ratio of orange juice at an FS temperature of 40 °C. Consistent with a previous study [65], Lukanin et al. [76] confirmed that UF is an effective method to clarify apple juice and reduce biopolymer content. In another investigation by Julian's research group [73], the effect of feed juice sources on VMD performance was explored. They found that the dewatering rate of model sugarcane juice was nearly twice that of raw industrial sugarcane juice, attributed to impurities present in the raw juice. Consequently, the final concentration of the model feed juice (73.3 Brix°) was higher than that of the raw juice (64.8 Brix°) after 15 h of operation (Fig. 5). Conversely, a recent study [72] reported an increase in permeate flux rates at lower and higher concentration ranges of clarified date juice FS, highlighting the significance of pretreated FS in fruit juice concentration using the MD process.

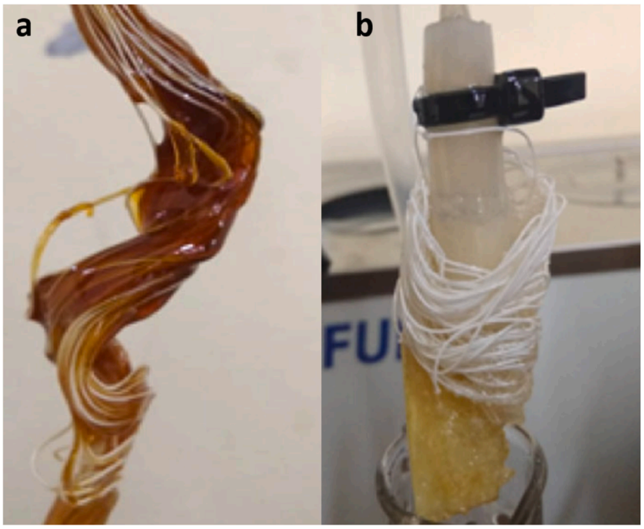

Fig. 5. Images of sugar crystal formed on the membrane surface of SVMD [73]: (a) Industrial raw sugarcane and (b) cane sugar model solution.

Considering the significant influence of FS parameters on MD performance, studies have highlighted the advancements of the VMD process in aroma recovery and fruit juice enrichment at low FS temperature, providing added value with reduced energy requirements for FS heating. On the other hand, higher FD concentrations have been found to induce membrane wettability and TP, resulting in weakened MD performance. Several studies emphasized the importance of FS pretreatment, such as UF, as a means to mitigate membrane fouling and enhance the dewatering rate in the MD process. These pretreatment methods have proven effective in reducing membrane wettability and improving MD performance for liquid food concentration.

2.3. Hybrid membrane-based systems in the food industry

Integrating membrane processes with other technologies is a viable approach to improve performance, reduce costs, and address operational challenges in liquid food processing [80]. While membrane processes offer advantages over traditional separation and concentration methods, standalone membrane processes may fall short in achieving the highest concentration factors compared to evaporation. Therefore, the application of hybrid membrane-based systems on an industrial scale becomes necessary to address issues such as fouling, scaling, and mechanical stability [81]. In a hybrid membrane-based system for food processing, one unit is dedicated to feeding stream clarification, such as MF and UF, while another unit focuses on the further concentration of the FS using technologies like RO, NF, FO, and MD. Additionally, the FO hybrid system incorporates a DS regeneration unit, which plays a crucial role in ensuring the sustainability of the FO process. By integrating different technologies, these hybrid systems offer enhanced performance and operational efficiency for liquid food processing.

However, research on hybrid systems combining FO and MD processes for food industry applications, particularly in the concentration of juices, is still limited and requires further investigation. For example, as indicated in Table 3, a recent study implemented an MD and crystallizer unit combination to concentrate industrial sugarcane juice and produce crystal sugar as the final product [73]. Wang et al. [27] also explored an integrated FO-MD hybrid system to concentrate bovine serum albumin (BSA) in a protein solution using a hollow fiber membrane (Fig. 6). They developed a simple mathematical model to predict the rate of protein concentration, independent of the initial protein concentration. Similarly, in another study [28], an integrated FO-MD process was employed to concentrate apple juice, resulting in reduced nutritional loss and improved efficiency compared to the RO process. It is worth noting that in the FO-MD hybrid system, the MD process plays a vital role in continuously reconcentrating the DS, ensuring its effectiveness.

Furthermore, Menchik and Moraru [82] successfully implemented an RO-FO hybrid system at an industrial scale to recover milk proteins from Greek yogurt acid whey. The FO process was employed to further concentrate the Greek yogurt acid whey beyond the separation limit of the RO process. This hybrid approach outperformed thermal evaporation, highlighting its potential for the food processing industry. In a subsequent study, the performance of UF-FO and MF-FO hybrid systems for apple juice concentration using FO was compared [83]. The results demonstrated similar FO performance when UF or MF processes were utilized as pretreatment methods.

Table 3 emphasizes the prevalence of hybrid membrane-based systems in FO studies for liquid food concentration. The MD process, on the other hand, has predominantly been employed as a DS recovery unit within the FO process. It is important to note that most studies investigating hybrid FO or MD systems have been conducted at the lab scale, necessitating further research to advance the maturity level of MD and FO hybrid systems for the concentration of liquid foods.

Table 3
Summary of the hybrid membrane-based system for the concentration of liquid food.

Hybrid system	Membrane module	Scale	Feed solution		Outcomes				Ref
			Source	*Brix °*	*Product*	*J_w (LMH)*	*Brix °*	*Energy consumption (kWh/kg water)*	
FO-MD	Flat sheet	Lab	Apple juice	10	Apple juice	5	45.1		[28]
RO	Spiral-wound	Pilot	Acid Whey	6.6	Greek Acid	3.6	19.6	0.29	[82]
FO					Yogurt	1.6	40.2	0.65	
MF/UF-FO	Flat sheet	Lab	Apple Juice		Apple juice	~2	65		[83]
FO/RO	Flat sheet	Lab	Cheese whey	6.7[b]	Whey		27[b]		[84]
FO-MD	Hollow fiber	Lab	Bovine Serum Albumin (BSA)	0.1[a]	Protein solution	~4	~3[a]		[27]
FO-NF	Flat sheet	Lab	Waste Cheese Whey	48.8[a]	whey protein		955[a]		[85]
FO-evaporation	Flat sheet	Lab	Grape juice	15.5	Grape juice	19.3	65.7		[58]
MD-crystallization	Hollow fiber	Lab	Raw Sugarcane juice	50	Sugar crystals		64.8		[73]

[a] Mass concentration (g/L), [b] Weight %

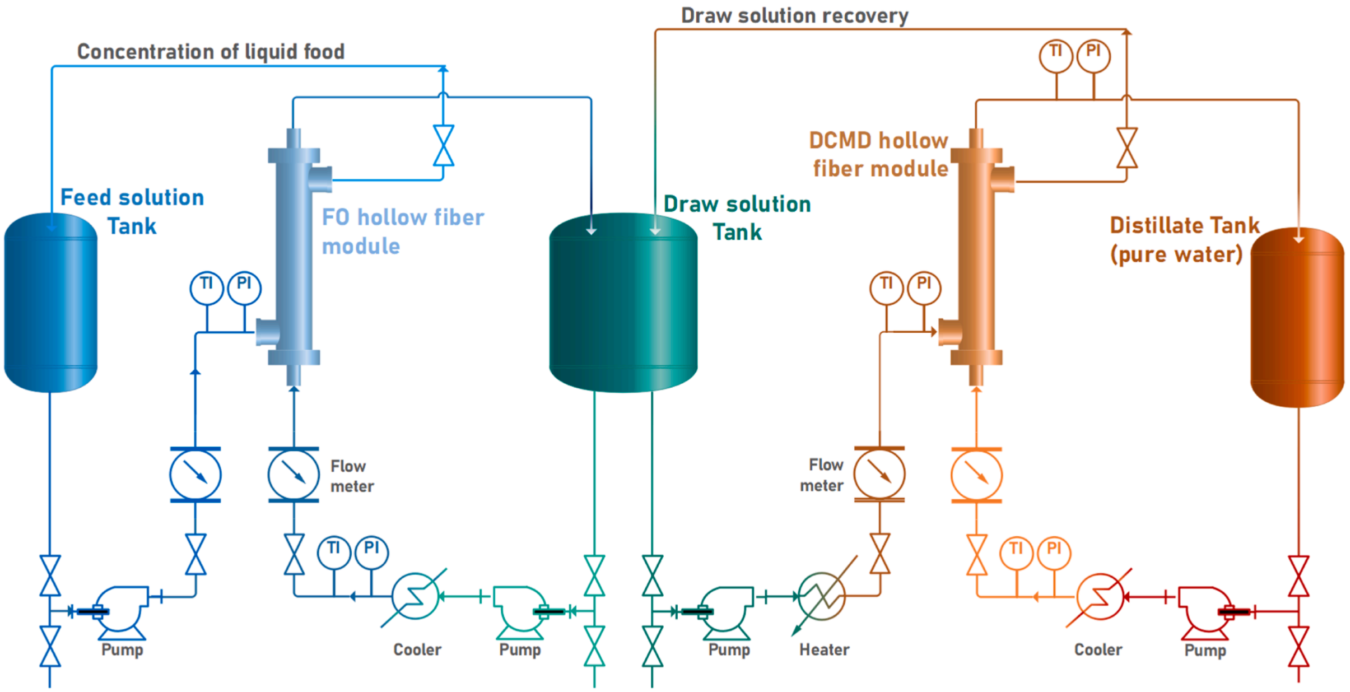

Fig. 6. Schematic diagram of FO-MD hybrid system for the concentration of liquid food of Hollow fiber membrane of FO and MD, adopted from [27].

3. Technology readiness level (TRL) of membrane-based processes for the concentration of liquid foods

The technology readiness level (TRL) of membrane-based processes for liquid food concentrations is evaluated based on the performance matrices outlined in Table 4**.** Most studies have focused on utilizing the FO process for the concentration of liquid foods, including juices and dairy products. On the other hand, research on the MD process has primarily centered around juice concentration and aroma compound recovery from fruit juice. It has been observed that the FO process can accommodate a wider range of initial juice concentrations (2–15 Brix°) [28,30,34,40,46,49,55,57,58,86], while VMD has been investigated at a higher initial concentration (50 Brix°) of the feed source [73]. From a practical standpoint, operating at a lower initial concentration of the FS is favorable for achieving a higher dewatering rate and minimizing fouling. Additionally, the study demonstrated the long-term operation capability of the FO process (up to 3 days) using a pilot-scale spiral-wound membrane module.

The FO process typically operates at a higher feed flow rate compared to the MD process. However, it should be noted that the MD

Table 4
Performance matrices of FO and MD processes for concentrating liquid foods [25–30,32–34,39,41,42,46,47,49–51,53–58,64,65,72–79,82–86].

Parameters	Method			
	FO	MD		
		DCMD	VMD	SGMD
Concentration of FS (Juices: Brix°, Whey/Milk: wt %)	2–15 Brix° 5.9–48.8 wt %	11–22 Brix°	12–50 Brix°	12 Brix°
Operating time (h)	1–72	2–20	6 &15	
Feed flowrate (LPM)	0.1–46	0.1	0.5 & 6.7	6.7
Membrane module	Flat sheet, Hollow fiber & Spiral-wound	Flat sheet & Hollow fiber	Flat sheet & Hollow fiber	Flat sheet
Concentration factor	1.1–22.6	2.3–5.7	1.4–21	12.1
Dewatering rate (LMH) of fruit juices/whey/milk	1–19.8	3–15	20.7	4.9

process consumes more energy than FO due to factors such as heating/cooling equipment and pumps involved in the specific energy consumption of MD. In contrast, the energy consumption in the FO process is primarily attributed to the pump unless additional components like a DS recovery unit or pressure-assisted osmosis (PAO) are required. Furthermore, it is worth mentioning that there is limited availability of techno-economic analysis for FO and MD studies concerning the concentration of liquid foods. Conducting such analysis is crucial for process optimization and obtaining realistic estimates of the operating costs before scaling up to larger production levels.

The TRL scale in Fig. 7 provides an overview of the transition of the FO and MD processes toward industrial-scale applications for liquid food concentration. The classification is based on process validation (modeling and simulation/experimental), process scale (lab/pilot), membrane module (flat/hollow fiber/spiral wound), feed source (simulated/commercial/raw), and operating time. Most studies on FO and MD processes fall within the TRL 4 and 7 range, as depicted in Fig. 7. The FO process has been extensively studied with different feed solutions and membrane modules. Around 53 % of these studies are at TRL 5, while only 19 % are at TRL 6. Despite the relatively recent exploration of FO in food processing, 11 % of the studies have reached TRL 7.

In contrast, the MD process has been applied in food processing since 1992. However, compared to the FO process, there have been relatively fewer investigations of MD for liquid food concentration. Most of the MD studies have been performed on a lab scale, with 28 % at TRL 4, 33 % at TRL 5 (33 %), and 39 % at TRL 6. This limited validation can be attributed to the shorter timeframe of MD research in liquid food concentration compared to FO. Furthermore, while the FO process for food processing has focused on addressing process challenges and developing mitigation methods to minimize membrane fouling, concentration polarization (CP), and reverse solute flux (RSF), the majority of these advancements have been made at the lab scale.

4. Outlook and future perspective

In recent years, FO and MD technologies have gained significant attention and have made remarkable progress in various industries, including the food sector. FO studies have focused on exploring different feed sources and assessing their suitability for liquid food concentration. These studies have also addressed critical challenges such as internal concentration polarization (ICP), membrane fouling, reverse solute flux (RSF), and DS recovery. Fig. 8a shows that recent FO research has prioritities DS recovery and the exploration of renewable DS types, such as food preservatives, additives, and gluconate salts, to mitigate RSF and preserve product quality. Membrane fabrication studies for FO have increasingly adopted phase inversion methods to achieve higher water permeability and lower salt coefficients. Moreover, FO studies have been applied to freshly made or raw liquid foods such as fruit juices, whey, and milk, promoting the need for appropriate pretreatment methods based on the characteristics of the specific feed source. Commonly employed pretreatment methods include UF [26,65,74,77,83], centrifuging (CEN) [29,30,46,76], and enzymatic treatment (ENZ) [47,72,77,79].

MD technology has shown promise for the concentration of juice and flavoring compounds in food processing. Researchers have extensively studied the operational parameters of MD and their impact on food processing. Fig. 9b highlights that the progress in MD for food processing has primarily focused on the use of hollow fiber membranes and the application of pretreatment methods for the FS.

Pretreating the FS before liquid food concentration using membrane-based processes is essential for ensuring membrane stability and process sustainability. Research on FO and MD for dewatering apple, blackcurrant, and date juices has demonstrated that employing two consecutive pretreatment methods (CEN/ENZ or ENZ/UF) leads to higher water flux and reduced fouling. Apple juice, for instance, contains pectin that can form a fouling gel layer on the FO membrane surface, compromising membrane performance. Therefore, significant attention has been given to investigating fouling control strategies, including various pretreatment methods and membrane cleaning approaches. Conversely, studies focusing on other fruit juices such as orange, grapefruit, grape juice, lime, and pineapple have shown favorable membrane fluxes and concentration factors when using CEN alone as the pretreatment method.

Unlike MD, FO research primarily focuses on methods for cleaning membranes used in liquid food concentration. For example, studies on dewatering orange and grape juices using the FO process have demonstrated effective membrane fouling mitigation through hydraulic flushing using DI water as the FS and DS. However, for other feed sources like whey, apple juice, and blackcurrant juice, chemical cleaning is necessary to remove the fouling layer and recover membrane flux. Nonetheless, chemical cleaning is not ideal for commercial application due to the additional chemical usage, potential impact on product quality, and the need for subsequent physical cleaning steps.

Despite several advancements in FO and MD processes for food processing, there are still obstacles that hinder their smooth transition to the industrial scale. One major challenge in the FO process is the impact

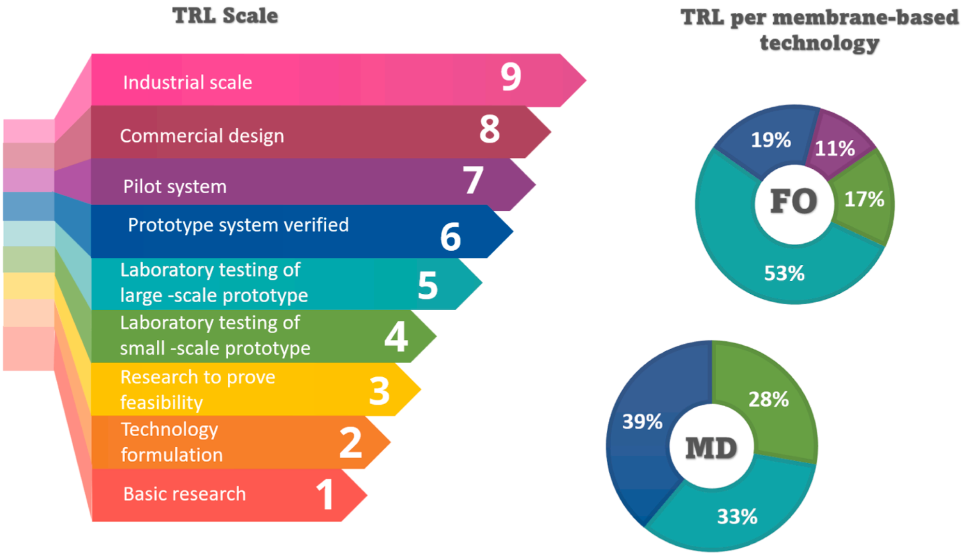

Fig. 7. Standard technology readiness level (TRL) scale (left): TRLs of FO and MD processes are discussed in Sections 2.1, 2.2, and 2.3.

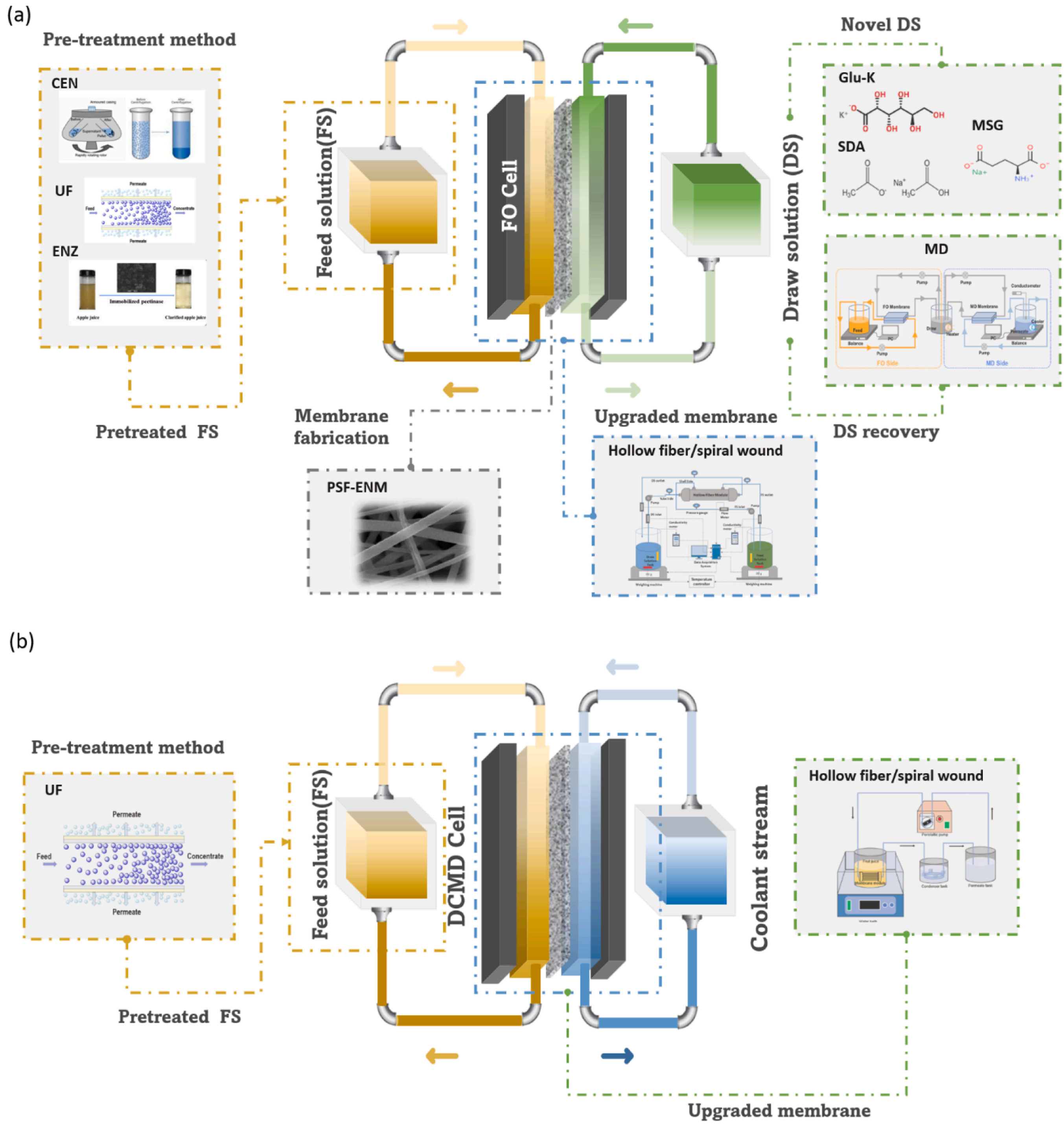

Fig. 8.. Illustration of studies for the past 22 years on the advancement of (a) FO process (novel DS [28,40,42,55,61], DS recovery [27,28,42], pretreatment [26,29,30,42,46,49,50,83], membrane fabrication [25,35,52,55,57], and upgraded membrane [35,48,53]) and (b) MD process (pretreatment [65], membrane fabrication [27,28], and upgraded membrane [64,65,73,77,79]).

of ICP on performance. However, only a small percentage (4 %) of FO studies (Fig. 9a) have utilized the electrospun method to fabricate nanofiber membranes, which helps mitigate the effects of ICP by enhancing the structural parameter of the support layer. Additionally, the development of the FO process extends beyond membrane fabrication and DS exploration. Few studies have investigated the application of PAO to assess the performance of FO. Considering the importance of product quality in the industry, PAO-FO is considered more practical than FO alone. However, it is worth noting that the PAO-FO process with its existing hydraulic pressure (2–10 bar) may require higher energy compared to the FO process without the DS recovery step (0.2–0.55kWh/m^3)[87].

Furthermore, it is noteworthy that the applied pressure range of 0–10 bar in PAO-FO is similar to that in the UF process. This similarity presents an opportunity to fully leverage the advantages of PAO-FO in food processing. However, further research is needed to optimize and fine-tune the pressure range for PAO-FO to maximize its potential. Currently, only a limited percentage of studies (13 %) have focused on PAO-FO in food processing, indicating the need for a deeper understanding of its overall performance and its potential to enhance the

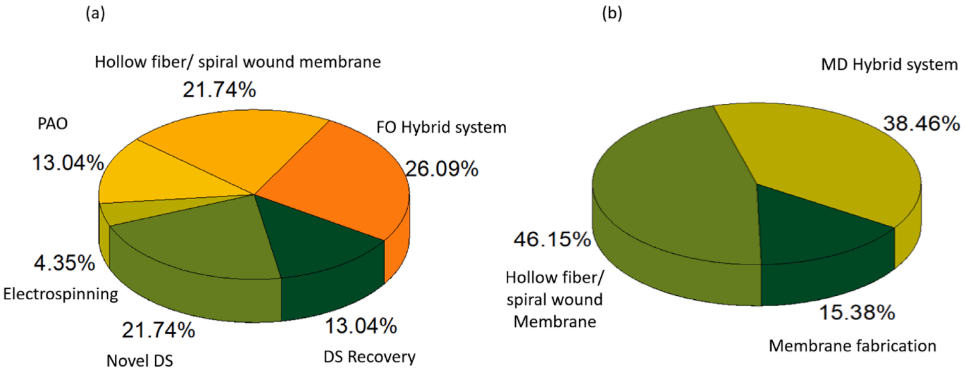

Fig. 9. Percentage of topics covered in published studies of (a) FO and (b) MD concerning food processing [25–30,32–34,39,41,42,46,47,49–51,53–58,64,65, 72–79,82–86].

quality, productivity, and cost-effectiveness of food processing techniques. Therefore, it is crucial to invest in extensive research and development efforts to explore innovative approaches for optimizing the pressure range of PAO-FO, which can bring revolutionary changes to the field of food processing. In addition, Fig. 9a highlights the limited attention given to DS recovery (13 %) in FO studies, resulting in a lack of practical knowledge and hindering the feasibility of implementing FO in the food industry. Addressing this significant research gap, including DS recovery, PAO, and membrane fabrication, should be a priority for future studies in this field.

Research activities on MD for liquid food concentration were halted between 2009 and 2021, but they have recently resumed in 2021 and 2022. However, the number of published research articles related to food processing (Fig. 9b) remains limited, providing insufficient quantifiable data on industrial-scale applications of the MD process in the food industry. In contrast to FO, the maturity level of MD studies in food processing is moderate, with approximately half of the studies utilizing a hollow fiber membrane, as shown in Fig. 9b. Interestingly, only 15 % of the membranes developed in MD studies are specifically used for DS recovery during liquid food concentration. Despite the significant challenges posed by membrane wetting and temperature polarization in MD, there have been no specific modifications or developments of hydrophobic membranes tailored for liquid food concentration using MD, based on our current knowledge. This highlights a significant research gap that should be addressed in future studies.

5. Conclusion

This study provides a comprehensive and critical review of modern membrane-based technologies in food processing and offers insights into their future industrial development. Recent advancements in membrane technology have highlighted the significance and benefits of FO and MD in food processing. The key conclusions drawn from this review are as follows:

- FO studies for liquid food concentration have primarily been conducted on a lab scale using commercial flat sheet CTA FO membranes and NaCl as the DS. Operating in FO mode has been found to result in less fouling compared to the PRO mode.
- Current research in FO focuses on exploring suitable DS options and the application of pressure-assisted osmosis (PAO) to manage food product quality and safety. Among the novel DS types, potassium gluconate has emerged as a promising alternative due to its lower salt diffusion to the feed side and higher dewatering flux compared to NaCl.
- DS recovery has received limited attention in liquid food processing using FO.
- In contrast to FO, MD studies have primarily been conducted on a lab scale, with a focus on using hollow fiber MD membranes for fruit juice and fragment concentration. This indicates a higher maturity level of the MD process in food processing.
- The development of MD to overcome wetting and temperature polarization issues in food processing is still limited, with most studies utilizing commercial MD membranes.
- Both FO and MD studies have confirmed the effectiveness of FS pretreatment in mitigating membrane fouling, enhancing membrane durability, and improving liquid food enrichment.
- To advance the maturity level of FO and MD processes in food processing, further research is needed on the implementation of hollow fiber and spiral wound membranes, as well as the development of hybrid membrane-based systems for liquid food concentration at a pilot scale.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dong Suk han reports financial support was provided by Qatar National Research Fund.

Data Availability

Data will be made available on request.

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