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Membrane processes used for removal of pharmaceuticals, hormones, endocrine disruptors and their metabolites from wastewaters: a review

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ABSTRACT

The presence of pharmaceuticals, hormones, endocrine disruptors, and their metabolites in aquatic environments has recently attracted particular attention due to their potential risks and adverse health effects. Membrane processes as widely used technologies in wastewater treatment have played a significance role in elimination of pharmaceuticals, hormones, endocrine disruptors, and their metabolites from wastewaters. In the current research, membrane processes which are used for the removal of these pollutants have been classified into three main categories, namely membrane filtration processes (UF, NF, and RO), membrane bioreactors (MBRs) (aerobic submerged and external systems), and membrane contactors (liquid–liquid extraction, supported liquid membranes, forward osmosis, and membrane distillation). Filtration processes have been applied for the removal of a large number of the contaminants; however, NF has been the most used one and the results were significant in most of the cases. Performance of MBRs has been also investigated for extensive number of contaminants. These systems have also showed great performance in many of the studies. Nevertheless, there are only a few researches on the removal of these pollutants by membrane contactors; thus, they have the potential for growth. Membrane processes have also been used in combination with other processes.

Keywords: Membrane filtration; Membrane bioreactor; Membrane contactor; Pharmaceutical pollutant; Wastewater

1. Introduction

In recent years, occurrence of pharmaceutical compounds in surface waters and wastewaters has caused environmental concern. Several papers have investigated the presence of the mentioned pollutants especially in wastewaters [1,2]. However, no legal requirements have been set for discharge of these persistent and biologically active substances into aquatic environments [2]. The presence of pharmaceuticals in water is attributed to personal hygiene products, pharmaceutical industry waste, hospital waste, and therapeutic drugs [3]. Concentrations of individual compounds and their derivatives are relatively low in drinking water and its sources (ng/L to μg/L) [4]. Despite low concentration, it has been a matter of public concern that these pollutants could be unintentionally ingested via drinking water. This is because most of these substances are pharmacologically and

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physiologically active, and therefore may affect homeostatic mechanisms in the human body at very low concentrations [5].

Among different wastewater treatment processes, the development of membrane-based processes is significant, since they offer three clear advantages over conventional techniques [6]:

(1) Separation is achieved without the requirement of a phase change; therefore, it is more energetically efficient than distillation.
(2) Unlike adsorptive separation processes, little or no accumulation takes place in the membrane process, as a result of which, it operates continuously under steady-state condition without necessitating regeneration cycles.
(3) Little or no chemical addition is required, unlike conventional clarification which generally relies on the addition of chemical coagulants and flocculants.

Although membrane processes are a relatively new type of separation technology, several membrane processes, particularly pressure-driven membrane processes including RO, NF, UF, and MF have already been applied in an industrial scale [7]. RO systems were the first type of membrane systems used in advanced wastewater treatment [8]. Generally, UF, NF, and RO processes have high efficiencies for the removal of conventional micro-pollutants and natural organic matter from aqueous solutions and groundwaters, even generating permeates during industrial wastewater treatments that can frequently be reused. Particularly, these technologies have been widely tested in recent studies for the elimination of pharmaceuticals with high efficiency. The main advantages of these pressure-driven membrane processes are the quality of the purified permeate, the moderate operating temperatures and the low energy requirements, the absence of chemicals, and the possibility to be combined with other separation processes [9].

Membrane bioreactors (MBRs) have also attracted serious attention for the treatment of municipal wastewater [10]. MBR technology, combining the biological degradation process using activated sludge with membrane filtration, serves several advantages over CAS systems. MBRs are more useful for disinfection purposes. They have smaller footprints and produce less sludge as well. Therefore, these systems result in better effluent qualities have longer sludge retention times (SRT) independent of hydraulic retention times and allow for the rapid start-up of biological processes [11,12]. MBRs have been used to remove pharmaceuticals from wastewater in several studies [2].

Membrane contactors have been studied since the mid-1980s for a wide range of applications, such as extraction of metal ions from industrial waste and hydrometallurgical process streams and recovery of sulfur aroma compounds from food industry wastewaters. Several different operations can be performed with these devices, e.g. liquid–liquid extraction, osmotic evaporation, and membrane distillation [13]. In recent studies, the removal of several pharmaceutical pollutants by membrane contactor processes such as liquid–liquid extraction and forward osmosis has been studied [14,15].

Regarding the significance of public concern on occurrence of pharmaceutical pollutants in aquatic environments and the position of membrane processes in wastewater treatment, a review is presented in the current research on application of membrane processes in the removal of these pollutants from wastewater.

1.1. Review framework

The survey drew data from papers published in international journals, regarding the membrane processes used for the removal of pharmaceuticals, hormones, endocrine disruptors, and their metabolites from wastewaters. In this study, the membrane processes used for the removal of these contaminants have been classified into three main groups, i.e. pressure-driven membrane processes (membrane filtrations), MBRs, and membrane contactors. Since the first two groups are relatively large, the data have been presented through tables. After each table, valuable highlights have been derived. The membrane processes which do not come into any of these major groups have been discussed in another section which comes after the main groups. Thereafter, papers which have discussed membrane processes in combination with other treatment processes have been summarized in a table.

2. Pressure-driven membrane processes

Pressure-driven membrane processes are similar to classical filtration with much finer mesh or much smaller pores to enable the separation of tiny particles, even molecules. In these processes, the separation of a mixture is achieved by the rejection of at least one component by the membrane and passage of the other components through the membrane [7].

The membrane filtration processes primarily used in wastewater treatment are classified as MF, UF, NF, and RO [8]. Table 1 compares some of the characteristics of these four processes.

The most important part of a membrane separation process is the membrane itself [18,19]. In filtration processes, membrane effectiveness depends on fouling, flux, and selectivity. In fact, a major concern for membranes applications is fouling phenomenon, i.e. reversible and irreversible blocking of pores by colloidal/particulate matter and in case of drinking water by macromolecules of natural organic matters [20]. Fouling limits the membrane performance, reduces the working life of the membrane, and increases the cleaning costs [21]. Generally, increasing the hydrophilicity of the membrane surfaces and pore walls can remarkably reduce or suppress the membrane fouling [22,23]. Flux is the volume of water that passes through a membrane per unit of time and per unit of surface area of the membrane; it is measured in either liter per square meter per hour or gallon per day per square feet and is affected by water temperature [8]. Flux depends on the membrane, application, and operating conditions and is usually a function of time too. In pressure-driven membrane processes, pressure-normalized flux of a membrane at a certain temperature (often 20°C) is also used. The selectivity of a membrane is generally expressed by the retention or rejection of specific substances [7].

High separation efficiency, low energy requirement, and simplicity of the operation with modern compact modules are advantages of the membrane filtration processes. Moreover, there is no need for any chemical substances to be added. It is also easy to increase the process capacity (modular system). In these systems, the separation occurs in the continuous mode and is carried out in mild environment conditions. Furthermore, membrane processes can get joined with other unit processes (hybrid processes) easily [24–27].

There are five principal configurations used in membrane processes: flat sheet, hollow fibers, tubular, spiral-wound cylinders, and rotating flat plates [8]. Each type has dark and bright sides. Hollow fibers are generally the cheapest on a per square meter basis; however it is harder to make very thin selective membrane layers in hollow fiber form than in flat sheet form. Furthermore, hollow fiber modules require more pretreatment of the feed than is usually required by capillary or spiral-wound modules [28].

Membrane filtration processes are widely used either separately or as a combination of membranes in series in wastewater reclamation/reuse and drinking water treatment to remove pharmaceuticals and endocrine disruptors. Several studies investigating the rejections of these pollutants have been published. Table 2 is an overview of these works.

According to Table 2, the following results can be obtained:

(1) Applications of several commercial membranes have been investigated; besides, laboratorial prepared polymeric membranes were also evaluated.
(2) Commercial membranes have been used in most of the studies.
(3) MF has not been employed. In fact, UF, NF, and RO have been the filtration processes which were used.
(4) NF has been the most used filtration process.
(5) Flat sheet has been the most common configuration.
(6) In most of the cases, RO could successfully reject more than 80% of each of the pollutants regardless of the membrane material.
(7) There have been cases in which UF could do no elimination; however, in some cases, removal efficiencies of more than 80% have been observed for UF process.
(8) In nanofiltration processes, the removal efficiencies have lied within a wide range.
(9) Generally, NF performance has been notable.
(10) NF90 seems to have carried out the best performance among nanofiltration membranes. In most of the studies, the removal efficiency obtained by NF90 has been in the range of 96–100% which indicates the great performance of this commercial membrane.

Table 1
Comparison of four membrane processes [7,16,17]

Membrane	RO Asymmetric	NF Asymmetric	UF Asymmetric	MF Asymmetric/symmetric
Thickness (μm)	150	150	150–250	10–150
Pore size	<1 nm	0.5–10 nm	1–100 nm	0.1–5 μm
Operating pressure (bar)	10–100	5–20	1–5	0.1–2
Flux range (L m^{-2} h^{-1} bar^{-1})	0.05–1.4	1.4–12	10–50	>50

Table 2
An overview of filtration processes used for the removal of pharmaceuticals, hormones, endocrine disruptors, and their metabolites

Therapeutic class	Removed pharmaceuticals, hormones, endocrine disruptors, and their metabolites	Membrane material	Initial concentration-source	Filtration type	Effective pore size	Commercial code	Configuration	Removal efficiency range	Refs.
Analgesics/anti-inflammatories	Acetaminophen	–	500 μg/L synthetic	NF		SR2	Flat sheet	30–65%	[29]
		–		NF		SR3	Flat sheet	11–58%	[29]
		Aromatic polyamide	5–18 μg/L surface water	NF	1 nm	NF-90	Flat sheet	77%	[30]
				NF	1.3 nm	NF-200	Flat sheet	23%	[30]
		Thin film composite with sulfonated polyethersulfone coated with an ultrathin polyimide	2–<150 ng/L surface water	UF		GM	Flat sheet	4%	[31]
		Thin film composite with aromaticpolyamide coated with an ultrathin polyimide		NF		ESNA	Flat sheet	26%	[31]
		–	18 ng/L effluent from a WWTP	UF	–	–	–	5%	[32]
	Aminopyrine	Thin film composite membranes with a cross-linked aromatic polyamide top layer	2–100 μg/L surface water	NF	–	Trisep TS-80	–	99%	[33]
				NF	–	Desal HL	–	97%	[33]
	Codeine	Polyethersulfone	5794 ng/L effluent from a WWTP	UF	–	PT	Flat sheet	79%	[34]
		Made of thin film polyamide		NF	–	HL	Flat sheet	94%	[34]
	Diclofenac	Polyethersulfone	0.025–0.1 μg/Linfluent of a DWTP	NF	–	FM NP010	Flat sheet	10–93%	[35]
		Thin film composite with sulfonated polyethersulfone coated with an ultrathin polyimide	2–<150 ng/L-surface water	UF		GM	Flat sheet	9%	[31]
		Thin film composite with aromatic polyamide coated with an ultrathin polyimide		NF		ESNA	Flat sheet	38%	[31]
		–	38 ng/L Effluent from a WWTP	UF	–	–	–	2.6%	[32]
		–	26 ng/L Saline ground water	RO	–	–	–	3.8%<	[32]
		Thin film composite membranes with a cross-linked aromatic polyamide top layer	2–5 μg/L surface water	NF	–	Trisep TS-80	–	100%	[33]
		Polyethersulfone	942 ng/L effluent from a WWTP	UF	–	PT	Flat sheet	71%	[34]
		Made of thin film polyamide		NF	–	HL	Flat sheet	92%	[34]
		–	115, 156 ng/L effluent from a	NF	–	UTC-60	Flat sheet	56–98%	[36]
		–	WWTP	RO	–	LF10	Flat sheet	90%	[36]
	Fenoprofen	Aromatic polyamide	5–18 μg/L surface water	NF	1 nm	NF-90	Flat sheet	94%	[30]
				NF	1.3 nm	NF-200	Flat sheet	90%	[30]
		Thin film composite membranes with a cross-linked aromatic polyamide top layer	2–100 μg/L surface water	NF	–	Trisep TS-80	–	96%	[33]
	Hydrocodone	–	105 ng/L Effluent from a WWTP	UF		–	–	14.3%	[32]
	Ibuprofen	Aromatic polyamide	5–18 μg/L surface water	NF	1 nm	NF-90	Flat sheet	96%	[30]
				NF	1.3 nm	NF-200	Flat sheet	89%	[30]
		Thin film composite with aromatic polyamide coated with an ultrathin polyimide	2–<150 ng/L surface water	NF		ESNA	Flat sheet	45%	[31]
		–	39 ng/L Effluent from a WWTP	UF	–	–	–	7.7%	[32]
		–	259, 302 ng/L Saline ground water	RO	–	–	–	90.3%<	[32]
		Thin film composite membranes with a cross-linked aromatic polyamide top layer	2–30 μg/L surface water	NF	–	Trisep TS-80	–	100%	[33]
				NF	–	Desal HL	–	99%	[33]
		Polyethersulfone	381 ng/L effluent from a WWTP	UF	–	PT	Flat sheet	69%	[34]
		Made of thin film polyamide		NF	–	HL	Flat sheet	88%	[34]
		Polyethersulfone	0.025–0.1 μg/L influent of a DWTP	NF	–	FM NP010	Flat sheet	10–92%	[35]
		Cellulose acetate	26.44 mg/L synthetic	NF	–	–	Flat sheet	54.3–59.1%	[37]
		Cellulose acetate membranes with 3 wt% charged surface modifying macromolecule additive synthesized by reactive diisocyanate and dihydroxy naphthalene disulfonate		NF	–	–	Flat sheet	48.2–48.4%	[37]
		Cellulose acetate membranes with a tailor made hydrophilic surface modifying macromolecule additive manufactured incorporating poly(ethylene glycol) as end groups		NF	–	–	Flat sheet	45.5–47.1%	[37]
		Cellulose acetate membrane developed by incorporating charged surface modifying macromolecules	140–4706 ng/L-influent of a WTP	NF	–	–	Flat sheet	27–80.4%	[38]
		–		NF	–	NF-270	–	75.3–90.5%	[38]
	Indomethacin	–	500 μg/L synthetic	NF		SR2	Flat sheet	82–95%	[29]
		–		NF		SR3	Flat sheet	95–100%	[29]

(*Continued*)

Table 2 (*Continued*)

Therapeutic class	Removed pharmaceuticals, hormones, endocrine disruptors, and their metabolites	Membrane material	Initial concentration-source	Filtration type	Effective pore size	Commercial code	Configuration	Removal efficiency range	Refs.
	Ketoprofen	Aromatic polyamide	5–18 μg/L surface water	NF	1 nm	NF-90	Flat sheet	94%	[30]
				NF	1.3 nm	NF-200	Flat sheet	91%	[30]
		Thin film composite membranes with a cross-linked aromatic polyamide top layer	2–50 μg/L surface water	NF	–	Trisep TS-80	–	100%	[33]
				NF	–	Desal HL	–	98–99%	[33]
		Polyethersulfone	608 ng/L effluent from a WWTP	UF	–	PT	Flat sheet	58%	[34]
		Made of thin film polyamide		NF	–	HL	Flat sheet	87%	[34]
		–	232, 267 ng/L effluent from a WWTP	NF	–	UTC-60	Flat sheet	55–96%	[36]
		–		RO	–	LF10	Flat sheet	97–100%	[36]
	Mefenamic acid	–	34, 42 ng/L effluent from a WWTP	NF	–	UTC-60	Flat sheet	55–94%	[36]
		–		RO	–	LF10	Flat sheet	87–100%	[36]
	Naproxen	Aromatic polyamide	5–18 μg/L surface water	NF	1 nm	NF-90	Flat sheet	94%	[30]
				NF	1.3 nm	NF-200	Flat sheet	90%	[30]
		Thin film composite with aromatic polyamide coated with an ultrathin polyimide	2–<150 ng/L surface water	NF		ESNA	Flat sheet	9%	[31]
		–	24 ng/L Effluent from a WWTP	UF	–	–	–	12.5%	[32]
		–	91, 118 ng/L Saline ground water	RO	–	–	–	78.8%<	[32]
		Polyethersulfone	384 ng/L effluent from a WWTP	UF	–	PT	Flat sheet	47%	[34]
		Made of thin film polyamide		NF	–	HL	Flat sheet	80%	[34]
		Made of thin film composite, with a cross-linked aromatic polyamide top layer	1.15 mg/L synthetic	UF	–	GK	Flat sheet	18–80%	[9]
		Made of cellulose acetate		NF	–	CK	Flat sheet	74–84%	[9]
	Phenacetin	Aromatic polyamide	5–18 μg/L surface water	NF	1 nm	NF-90	Flat sheet	71%	[30]
				NF	1.3 nm	NF-200	Flat sheet	40%	[30]
		Made of thin film composite, with a cross-linked aromatic polyamide top layer	0.896 mg/L synthetic	UF	–	GK	Flat sheet	6–14%	[9]
		Made of cellulose acetate		NF	–	CK	Flat sheet	3–5%	[9]
	Phenazone (antipyrine)	Aromatic polyamide	5–18 μg/L surface water	NF	1 nm	NF-90	Flat sheet	92%	[30]
				NF	1.3 nm	NF-200	Flat sheet	75%	[30]
		Thin film composite membranes with a cross-linked aromatic polyamide top layer	2–100 μg/L surface water	NF	–	Trisep TS-80	–	94%	[33]
				NF	–	Desal HL	–	84%	[33]
		Polyethersulfone	140 ng/L effluent from a WWTP	UF	–	PT	Flat sheet	54%	[34]
		Made of thin film polyamide		NF	–	HL	Flat sheet	82%	[34]
Anthelmintics	Febantel	Polyamide	10 mg/L synthetic (using Milli-Q water, model water, tap water, and real pharmaceutical wastewater)	NF	0.79 nm	NF90	Flat sheet	99–99.9%<	[39]
				NF	0.72, 1.56 nm	NF270	Flat sheet	87–99.9%<	[39]
				NF	0.72, 1.56 nm	NF	Flat sheet	94–99.9%<	[39]
				NF	0.73, 1.56 nm	HL	Flat sheet	92–99.9%<	[39]
				RO	0.78 nm	LFC1	Flat sheet	98–99.9%<	[39]
				RO	0.88 nm	XLE	Flat sheet	99–99.9%<	[39]
Antibiotics	Amoxicillin	Made of polyethersulfone	1.83 mg/L synthetic	UF	–	PT	Flat sheet	9%	[9]
		Made of thin film composite, with a cross-linked aromatic polyamide top layer		UF	–	GK	Flat sheet	13–40%	[9]
		Made of cellulose acetate		NF	–	CK	Flat sheet	86–98%	[9]
		Made of thin film polyamide		NF	–	HL	Flat sheet	97%	[9]
		–	500 μg/L synthetic	NF		SR2	Flat sheet	62–64.9%	[29]
		–		NF		SR3	Flat sheet	95–99%	[29]
		Modified polyethersulfone by addition of different concentrations of hydrophilic surfactant	20, 400 mg/L synthetic	NF	–	–	Flat sheet	15–99%	[40]
	Cephalexin	–	500 μg/L synthetic	NF		SR2	Flat sheet	48.4–100%	[29]
		–		NF		SR3	Flat sheet	21.2–98%	[29]
		Polyamide-imide	200 mg/L synthetic	UF	2.82 nm	–	Hollow fiber	<20%	[41]
		A novel thin film composite membrane fabricated by interfacial polymerization of hyperbranched polyethyleneimine and isophthaloyl chloride		NF	–	–	Hollow fiber	77–95%	[41]
	Ciprofloxacin	Polyethersulfone	229 ng/L effluent from a WWTP	UF	–	PT	Flat sheet	65%	[34]
		Made of thin film polyamide		NF	–	HL	Flat sheet	Not Determined	[34]
		Polyamide		NF	0.79 nm	NF90	Flat sheet	99–99.9%<	[39]
				NF		NF270	Flat sheet	79–99.9%<	[39]

(*Continued*)

Table 2 (*Continued*)

Therapeutic class	Removed pharmaceuticals, hormones, endocrine disruptors, and their metabolites	Membrane material	Initial concentration-source	Filtration type	Effective pore size	Commercial code	Configuration	Removal efficiency range	Refs.
			10 mg/L synthetic (using Milli-Q water, model water, tap water, and real pharmaceutical wastewater)	NF	0.72, 1.56 nm	NF	Flat sheet	91–99.9%<	[39]
				NF	0.73, 1.56 nm	HL	Flat sheet	94–99.9%<	[39]
				RO	0.78 nm	LFC1	Flat sheet	98–99.9%<	[39]
				RO	0.88 nm	XLE	Flat sheet	98–99.9%<	[39]
	Enrofloxacin	–	10 mg/L synthetic	RO	0.67 nm	HR95	–	98.8–100%	[42]
		–		RO	0.67 nm	XLE	–	97.2–100%	[42]
		–		RO	0.82 nm	TFC-S	–	100	[42]
		–		NF	0.82 nm	NF90	–	99.1–100%	[42]
		–		NF	1.02 nm	HL Desal	–	99.4–100%	[42]
	Erythromycin-H_2O	Thin film composite with sulfonated polyethersulfone coated with an ultrathin polyimide	2–<150 ng/L surface water	UF		GM	Flat sheet	63%	[31]
		Thin film composite with aromaticpolyamide coated with an ultrathin polyimide		NF		ESNA	Flat sheet	56%	[31]
		–	289 ng/L Effluent from a WWTP	UF	–	–	–	15.2%	[32]
	Levamisole	–	10 mg/L synthetic	RO	0.67 nm	HR95	–	96.8%	[42]
		–		RO	0.67 nm	XLE	–	99.4%	[42]
		–		NF	0.82 nm	NF90	–	99.9%	[42]
		–		NF	1.02 nm	HL Desal	–	69%	[42]
	Metronidazole	Aromatic polyamide	5–18 μg/L surface water	NF	1 nm	NF-90	Flat sheet	71%	[30]
				NF	1.3 nm	NF-200	Flat sheet	45%	[30]
		Polyethersulfone	135 ng/L effluent from a WWTP	UF	–	PT	Flat sheet	73%	[34]
		Made of thin film polyamide		NF	–	HL	Flat sheet	81%	[34]
	Ofloxacin	Polyethersulfone	285 ng/L effluent from a WWTP	UF	–	PT	Flat sheet	Not Determined	[34]
		Made of thin film polyamide		NF	–	HL	Flat sheet	95%	[34]
	Oxytetracycline	–	10 mg/L synthetic	RO	0.67 nm	HR95PP	–	99.3–100%	[42]
		–		RO	0.67 nm	XLE	–	99.2–100%	[42]
		–		RO	0.82 nm	TFC-S	–	100%	[42]
		–		NF	0.82 nm	NF90	–	99–100%	[42]
		–		NF	1.02 nm	HL Desal	–	99.2–100%	[42]
	Praziquantel	–	10 mg/L-synthetic	RO	0.67 nm	HR95PP	–	99.9–100%	[42]
		–		RO	0.67 nm	XLE	–	99.6–100%	[42]
		–		RO	0.82 nm	TFC-S	–	100%	[42]
		–		NF	0.82 nm	NF90	–	99–100%	[42]
		–		NF	1.02 nm	HL Desal	–	98.4–100%	[42]
	Sulfadiazine	–	10 mg/L-synthetic	RO	0.67 nm	HR95PP	–	99.4–100%	[42]
		–		RO	0.67 nm	XLE	–	99.4–100%	[42]
		–		RO	0.82 nm	TFC-S	–	100%	[42]
		–		NF	0.82 nm	NF90	–	99.4–100%	[42]
		–		NF	1.02 nm	HL Desal	–	85.6–90.3%	[42]
	Sulfaguanidine	–	10 mg/L-synthetic	RO	0.67 nm	HR95PP	–	98.9–100%	[42]
		–		RO	0.67 nm	XLE	–	99.3–100%	[42]
		–		RO	0.82 nm	TFC-S	–	100%	[42]
		–		NF	0.82 nm	NF90	–	99.1–100%	[42]
		–		NF	1.02 nm	HL Desal	–	34.9–67.3%	[42]
	Sulfamethazine	Cellulose acetate	38.65 mg/L-synthetic	NF	–	–	Flat sheet	85.2–86.2%	[37]
		Cellulose acetate membranes with 3 wt% charged surface modifying macromolecule additive synthesized by reactive diisocyanate and dihydroxy naphthalene disulfonate		NF	–	–	Flat sheet	84.1–87.5%	[37]
		Cellulose acetate membranes with a tailor made hydrophilic surface modifying macromolecule additive manufactured incorporating poly(ethylene glycol) as end groups		NF	–	–	Flat sheet	77.3–78.6%	[37]
		Cellulose acetate membrane developed by incorporating charged surface modifying macromolecules	142, 8053 ng/L influent of a WTP	NF	–	–	Flat sheet	68.7–72.4%	[38]
				NF	–	NF-270	–	88.4–89%	[38]
		–	10 mg/L synthetic	RO	0.67 nm	HR95PP	–	99.3–100%	[42]
		–		RO	0.67 nm	XLE	–	99.1–100%	[42]

(*Continued*)

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Therapeutic class	Removed pharmaceuticals, hormones, endocrine disruptors, and their metabolites	Membrane material	Initial concentration-source	Filtration type	Effective pore size	Commercial code	Configuration	Removal efficiency range	Refs.
		–		RO	0.82 nm	TFC-S	–	100%	[42]
		–		NF	0.82 nm	NF90	–	99.4–100%	[42]
		–		NF	1.02 nm	HL Desal	–	87.4–96.3%	[42]
	Sulfamethoxazole	Aromatic polyamide	5–18 μg/L surface water	NF	1 nm	NF-90	Flat sheet	95%	[30]
				NF	1.3 nm	NF-200	Flat sheet	83%	[30]
		Thin film composite with sulfonated polyethersulfone coated with an ultrathin polyimide	2–<150 ng/L surface water	UF		GM	Flat sheet	2%	[31]
		Thin film composite with aromaticpolyamide coated with an ultrathin polyimide		NF		ESNA	Flat sheet	32%	[31]
		–	66 ng/L Effluent from a WWTP	UF	–	–	–	4.5%	[32]
		Polyethersulfone	363 ng/L effluent from a WWTP	UF	–	PT	Flat sheet	87%	[34]
		Made of thin film polyamide		NF	–	HL	Flat sheet	95%	[34]
		Polyamide	10 mg/L synthetic (using Milli-Q water, model water, tap water, and real pharmaceutical wastewater)	NF	0.79 nm	NF90	Flat sheet	96–99.9%<	[39]
				NF	0.72, 1.56 nm	NF270	Flat sheet	15.4–87%	[39]
				NF	0.72, 1.56 nm	NF	Flat sheet	29.4–89.2%	[39]
				NF	0.73, 1.56 nm	HL	Flat sheet	24.7–91%	[39]
				RO	0.78 nm	LFC1	Flat sheet	95–99.9%<	[39]
				RO	0.88 nm	XLE	Flat sheet	88–98.9%	[39]
	Tetracycline	–	500 μg/L synthetic	NF		SR2	Flat sheet	74–97%	[29]
		–		NF		SR3	Flat sheet	63–100%	[29]
	Trimethoprim	Thin film composite with sulfonated polyethersulfone coated with an ultrathin polyimide	2–<150 ng/L surface water	UF		GM	Flat sheet	22%	[31]
		Thin film composite with aromaticpolyamide coated with an ultrathin polyimide		NF		ESNA	Flat sheet	56%	[31]
		–	138 ng/L Effluent from a WWTP	UF	–	–	–	18.1%	[32]
		–	265, 278 ng/L Saline ground water	RO	–	–	–	90.6%<	[32]
		Polyethersulfone	521 ng/L effluent from a WWTP	UF	–	PT	Flat sheet	74%	[34]
		Made of thin film polyamide		NF	–	HL	Flat sheet	86%	[34]
		–	10 mg/L synthetic	RO	0.67 nm	HR95PP	–	98.2–100%	[42]
		–		RO	0.67 nm	XLE	–	98.6–100%	[42]
		–		RO	0.82 nm	TFC-S	–	100%	[42]
		–		NF	0.82 nm	NF90	–	99.2–100%	[42]
		–		NF	1.02 nm	HL Desal	–	88.8–100%	[42]
		Polyamide	10 mg/L synthetic (using Milli-Q water, model water, tap water, and real pharmaceutical wastewater)	NF	0.79 nm	NF90	Flat sheet	97.9–99.9% <	[39]
				NF	0.72, 1.56 nm	NF270	Flat sheet	32–86.9%	[39]
				NF	0.72, 1.56 nm	NF	Flat sheet	64–94%	[39]
				NF	0.73, 1.56 nm	HL	Flat sheet	65.6–89%	[39]
				RO	0.78 nm	LFC1	Flat sheet	96–99.3%	[39]
				RO	0.88 nm	XLE	Flat sheet	90–99.2%	[39]
Antidepressants	Fluoxetine	–	45 ng/L Effluent from a WWTP	UF	–	–	–	68.9%	[32]
		–	263, 564 ng/L Saline ground water	RO	–	–	–	90.5%<	[32]
Antiepileptics	Carbamazepine	Aromatic polyamide	5–18 μg/L surface water	NF	1 nm	NF-90	Flat sheet	90%	[30]
				NF	1.3 nm	NF-200	Flat sheet	82%	[30]
		Thin film composite with sulfonated polyethersulfone coated with an ultrathin polyimide	2–<150 ng/L-surface water	UF		GM	Flat sheet	2%	[31]
		Thin film composite with aromaticpolyamide coated with an ultrathin polyimide		NF		ESNA	Flat sheet	47%	[31]
		–	191 ng/L Effluent from a WWTP	UF	–	–	–	15.7%	[32]
		Thin film composite membranes with a cross-linked aromatic polyamide top layer	2–25 μg/L surface water	NF	–	Trisep TS-80	–	96%	[33]
				NF	–	Desal HL	–	88%	[33]
		Polyethersulfone	169 ng/L effluent from a WWTP	UF	–	PT	Flat sheet	56%	[34]
		Made of thin film polyamide		NF	–	HL	Flat sheet	81%	[34]

(*Continued*)

Table 2 (*Continued*)

Therapeutic class	Removed pharmaceuticals, hormones, endocrine disruptors, and their metabolites	Membrane material	Initial concentration-source	Filtration type	Effective pore size	Commercial code	Configuration	Removal efficiency range	Refs.
		–	116, 136 ng/L effluent from a	NF	–	UTC-60	Flat sheet	20–99%	[36]
		–	WWTP	RO	–	LF10	Flat sheet	85–100%	[36]
		Polyethersulfone	0.025–0.1 μg/L influent of a DWTP	NF	–	FM NP010	Flat sheet	10–92%	[35]
		Cellulose acetate	26.25 mg/L synthetic	NF	–	–	Flat sheet	60.1–60.2%	[37]
		Cellulose acetate membranes with 3 wt% charged surface modifying macromolecule additive synthesized by reactive diisocyanate and dihydroxy naphthalene disulfonate		NF	–	–	Flat sheet	64–65.6%	[37]
		Cellulose acetate membranes with a tailor made hydrophilic surface modifying macromolecule additive manufactured incorporating poly(ethylene glycol) as end groups		NF	–	–	Flat sheet	46.6–51.4%	[37]
		Cellulose acetate membrane developed by incorporating charged surface modifying macromolecules	75–8053 ng/L-influent of a WTP	NF	–	–	Flat sheet	15.9–34%	[38]
		–		NF	–	NF-270	–	53.6–76.5%	[38]
		–	2–1300 μg/L synthetic	NF	–	NF270	Flat sheet	44–95%	[43]
		–	0.8 mg/L synthetic	RO	–	BW	Flat sheet	98–100%	[43]
		–		RO	–	SW	Flat sheet	98–100%	[43]
		–		RO	–	XLE	Flat sheet	97.6%	[43]
	Dilantin	–	130 ng/L Effluent from a WWTP	UF	–	–	–	24.6%	[32]
			239, 259 ng/L Saline ground water	RO	–	–	–	>90%	[32]
	Primidone	Polyethersulfone	117 ng/L effluent from a WWTP	UF	–	PT	Flat sheet	25%	[34]
		Thin film polyamide		NF	–	HL	Flat sheet	72%	[34]
		–	45, 55 ng/L effluent from a WWTP	NF	–	UTC-60	Flat sheet	27–84%	[36]
		–		RO	–	LF10	Flat sheet	86–99%	[36]
Antineoplastics	Cyclophosphamide	Thin film composite membranes with a cross-linked aromatic polyamide top layer	2–100 μg/L surface water	NF	–	Trisep TS-80	–	100%	[33]
				NF	–	Desal HL	–	94%	[33]
Anxiolytic sedatives hypnotics and antipsychotics	Diazepam	Thin film composite with sulfonated polyethersulfone coated with an ultrathin polyimide	2–<150 ng/L surface water	UF		GM	Flat sheet	4%	[31]
		Thin film composite with aromaticpolyamide coated with an ultrathin polyimide		NF		ESNA	Flat sheet	50%	[31]
		–	58 ng/L Effluent from a WWTP	UF	–	–	–	84%	[32]
	Meprobamate	Thin film composite with aromaticpolyamide coated with an ultrathin polyimide	2–<150 ng/L surface water	NF		ESNA	Flat sheet	37%	[31]
		–	561 ng/L Effluent from a WWTP	UF	–	–	–	5.7%	[32]
Bronchodilators and anti-asthma Drugs	Caffeine	Aromatic polyamide	5–18 μg/L synthetic	NF	1 nm	NF-90	Flat sheet	91%	[30]
				NF	1.3 nm	NF-200	Flat sheet	67%	[30]
		Thin film composite with sulfonated polyethersulfone coated with an ultrathin polyimide	2–<150 ng/L-surface water	UF		GM	Flat sheet	1%	[31]
		Thin film composite with aromaticpolyamide coated with an ultrathin polyimide		NF		ESNA	Flat sheet	29%	[31]
		–	85 ng/L Effluent from a WWTP	UF	–	–	–	7%	[32]
		–	196, 311 ng/L Saline ground water	RO	–	–	–	83.3%	[32]
	Clenbuterol	Thin film composite membranes with a cross-linked aromatic polyamide top layer	2–2.5 μg/L surface water	NF	–	Trisep TS-80	–	90%	[33]
				NF	–	Desal HL	–	88%	[33]
	Salbutamol	Thin film composite membranes with a cross-linked aromatic polyamide top layer	2–3 μg/L surface water	NF	–	Trisep TS-80	–	92%	[33]
				NF	–	Desal HL	–	94%	[33]
	Terbutaline	Thin film composite membranes with a cross-linked aromatic polyamide top layer	2–40 μg/L surface water	NF	–	Trisep TS-80	–	100%	[33]
				NF	–	Desal HL	–	87–93%	[33]
Cardiovascular drugs	Atenolol	Thin film composite membranes with a cross-linked aromatic polyamide top layer	2–50 μg/L surface water	NF	–	Trisep TS-80	–	91%	[33]
				NF	–	Desal HL	–	88–95%	[33]
		Polyethersulfone	1435 ng/L effluent from a WWTP	UF	–	PT	Flat sheet	11%	[34]
		Made of thin film polyamide		NF	–	HL	Flat sheet	76%	[34]
	Bezafibrate	Thin film composite membranes with a cross-linked aromatic polyamide top layer	2–50 μg/L surface water	NF	–	Trisep TS-80	–	100%	[33]
				NF	–	Desal HL	–	99–100%	[33]
		Polyethersulfone	288 ng/L effluent from a WWTP	UF	–	PT	Flat sheet	70%	[34]
		Made of thin film polyamide		NF	–	HL	Flat sheet	91%	[34]
	Clofibric acid		2–100 μg/L surface water	NF	–	Trisep TS-80	–	100%	[33]

(*Continued*)

Table 2 (*Continued*)

Therapeutic class	Removed pharmaceuticals, hormones, endocrine disruptors, and their metabolites	Membrane material	Initial concentration-source	Filtration type	Effective pore size	Commercial code	Configuration	Removal efficiency range	Refs.
		Thin film composite membranes with a cross-linked aromatic polyamide top layer		NF	–	Desal HL	–	99%	[33]
		–	32, 80 ng/L effluent from a WWTP	NF	–	UTC-60	Flat sheet	56–90%	[36]
		–		RO	–	LF10	Flat sheet	78–100%	[36]
	Fenofibric acid	Polyethersulfone	180 ng/L effluent from a WWTP	UF	–	PT	Flat sheet	86%	[34]
		Made of thin film polyamide		NF	–	HL	Flat sheet	88%	[34]
	Furosemide	Polyethersulfone	451 ng/L effluent from a WWTP	UF	–	PT	Flat sheet	70%	[34]
		Made of thin film polyamide		NF	–	HL	Flat sheet	78%	[34]
	Gemfibrozil	Aromatic polyamide	5–18 μg/L surface water	NF	1 nm	NF-90	Flat sheet	95%	[30]
				NF	1.3 nm	NF-200	Flat sheet	90%	[30]
		Thin film composite with aromaticpolyamide coated with an ultrathin polyimide	2–<150 ng/L surface water	NF		ESNA	Flat sheet	45%	[31]
		–	82 ng/L Effluent from a WWTP	UF	–	–	–	No Elimination	[32]
		–	230, 234 ng/L Saline ground water	RO	–	–	–	89.1%<	[32]
		Thin film composite membranes with a cross-linked aromatic polyamide top layer	2–100 μg/L surface water	NF	–	Trisep TS-80	–	100%	[33]
				NF	–	Desal HL	–	99–100%	[33]
		Polyethersulfone	1280 ng/L effluent from a WWTP	UF	–	PT	Flat sheet	59%	[34]
		Made of thin film polyamide	1280 ng/L effluent from a WWTP	NF	–	HL	Flat sheet	85%	[34]
	Hydrochlorothiazide	Polyethersulfone	2358 ng/L effluent from a WWTP	UF	–	PT	Flat sheet	44%	[34]
		Made of thin film polyamide		NF	–	HL	Flat sheet	56%	[34]
	Metoprolol	Thin film composite membranes with a cross-linked aromatic polyamide top layer	2–80 μg/L surface water	NF	–	Trisep TS-80	–	90%	[33]
				NF	–	Desal HL	–	90–94%	[33]
		Made of thin film composite, with a cross-linked aromatic polyamide top layer	1.34 mg/L-synthetic	UF	–	GK	Flat sheet	14–60%	[9]
		Made of cellulose acetate		NF	–	CK	Flat sheet	83–84%	[9]
	Pentoxifylline	Thin film composite with sulfonated polyethersulfone coated with an ultrathin polyimide	2–<150 ng/L surface water	UF		GM	Flat sheet	4%	[31]
		Thin film composite with aromaticpolyamide coated with an ultrathin polyimide		NF		ESNA	Flat sheet	38%	[31]
		–	49 ng/L Effluent from a WWTP	UF	–	–	–	10.2%	[32]
		–	169, 458 ng/L Saline ground water	RO	–	–	–	90.2%	[32]
		Thin film composite membraneswith a cross-linked aromatic polyamide top layer	2–100 μg/L surface water	NF	–	Trisep TS-80	–	99%	[33]
			2–100 μg/L surface water	NF	–	Desal HL	–	95%	[33]
	Pindolol	Thin film composite membranes with a cross-linked aromatic polyamide top layer	2–50 μg/L surface water	NF	–	Trisep TS-80	–	93%	[33]
			2–50 μg/L surface water	NF	–	Desal HL	–	74–82%	[33]
	Pravastatin	Polyethersulfone	136 ng/L effluent from a WWTP	UF	–	PT	Flat sheet	73%	[34]
		Made of thin film polyamide		NF	–	HL	Flat sheet	95%	[34]
	Propranolol	Thin film composite membranes with a cross-linked aromatic polyamide top layer	2–100 μg/L surface water	NF	–	Trisep TS-80	–	87%	[33]
				NF	–	Desal HL	–	75–88%	[33]
	Sotalol	Thin film composite membranes with a cross-linked aromatic polyamide top layer	2–2.5 μg/L surface water	NF	–	Trisep TS-80	–	93%	[33]
				NF	–	Desal HL	–	90%	[33]
Contrast media	Diatrizoate	–	0.7, 4 mg/L synthetic	NF		NF90	Flat sheet	97–98%	[43]
		–	0.6, 1 mg/L synthetic	NF		NF270	Flat sheet	96–97%	[43]
		–	0.8 mg/L synthetic	RO		BW	Flat sheet	100%	[43]
		–	0.8 mg/L synthetic	RO		SW	Flat sheet	100%	[43]
		–	0.7 mg/L synthetic	RO		XLE	Flat sheet	96–99%	[43]
	Iopamidol	Polyethersulfone	2831 ng/L effluent from a WWTP	UF	–	PT	Flat sheet	Not Determined	[34]
		Thin film polyamide		NF	–	HL	Flat sheet	64%	[34]
	Iopromide	Thin film composite with sulfonated polyethersulfone coated with an ultrathin polyimide	2–<150 ng/L surface water	UF		GM	Flat sheet	39%	[31]
		Thin film composite with aromaticpolyamide coated with an ultrathin polyimide		NF		ESNA	Flat sheet	57%	[31]
		–	75 ng/L Effluent from a WWTP	UF	–	–	–	No Elimination	[32]
		–	125, 165 ng/L Saline ground water	RO	–	–	–	84.4%	[32]
		Polyethersulfone	2946 ng/L effluent from a WWTP	UF	–	PT	Flat sheet	Not Determined	[34]
		Thin film polyamide		NF	–	HL	Flat sheet	86%	[34]

(*Continued*)

Table 2 (*Continued*)

Therapeutic class	Removed pharmaceuticals, hormones, endocrine disruptors, and their metabolites	Membrane material	Initial concentration-source	Filtration type	Effective pore size	Commercial code	Configuration	Removal efficiency range	Refs.
Corticosteroids	Dexamethasone	Polyamide	10 mg/L synthetic (using Milli-Q water, model water, tap water, and real pharmaceutical wastewater)	NF	0.79 nm	NF90	Flat sheet	99–99.4%	[39]
				NF	0.72, 1.56 nm	NF270	Flat sheet	64–99.9%<	[39]
				NF	0.72, 1.56 nm	NF	Flat sheet	89–99.9%<	[39]
				NF	0.73, 1.56 nm	HL	Flat sheet	96–99.9%<	[39]
				RO	0.78 nm	LFC1	Flat sheet	97–99.2%<	[39]
				RO	0.88 nm	XLE	Flat sheet	96–99.9%<	[39]
Disinfectants and preservatives	Triclosan	Thin film composite with sulfonated polyethersulfone coated with an ultrathin polyimide	2-<150 ng/L-surface water	UF		GM	Flat sheet	86%	[31]
		Thin film composite with aromaticpolyamide coated with an ultrathin polyimide		NF		ESNA	Flat sheet	90%	[31]
		–	32 ng/L Effluent from a WWTP	UF	–	–	–	87.5%	[32]
		–	166, 246 ng/L Saline ground water	RO	–	–	–	89.8%<	[32]
Endocrine disruptors	Bisphenol A	Aromatic polyamide	5–18 μg/L surface water	NF	1 nm	NF-90	Flat sheet	89%	[30]
				NF	1.3 nm	NF-200	Flat sheet	57%	[30]
Gastrointestinal drugs	Ranitidine	Polyethersulfone	225 ng/L effluent from a WWTP	UF		PT	Flat sheet	28%	[34]
		Made of thin film polyamide		NF		HL	Flat sheet	75%	[34]
Hormones and their modulators and estrogens	Androstenedione	Thin film composite with sulfonated polyethersulfone coated with an ultrathin polyimide	2–<150 ng/L surface water	UF		GM	Flat sheet	32%	[31]
		Thin film composite with aromaticpolyamide coated with an ultrathin polyimide		NF		ESNA	Flat sheet	56%	[31]
		–	77 ng/L Effluent from a WWTP	UF	–	–	–	71%	[32]
		–	247, 284 ng/L Saline ground water	RO	–	–	–	91%<	[32]
	17-ethinyl-estradiol	Aromatic polyamide	5–18 μg/L surface water	NF	1 nm	NF-90	Flat sheet	91%	[30]
				NF	1.3 nm	NF-200	Flat sheet	89%	[30]
	17ß-estradiol	Aromatic polyamide	5–18 μg/L surface water	NF	1 nm	NF-90	Flat sheet	96%	[30]
				NF	1.3 nm	NF-200	Flat sheet	84%	[30]
	Estradiol	–	87 ng/L Effluent from a WWTP	UF	–	–	–	98.8%<	[32]
		–	27, 125 ng/L Saline ground water	RO	–	–	–	80%<	[32]
		Thin film composite with sulfonated polyethersulfone coated with an ultrathin polyimide	2–<150 ng/L surface water	UF		GM	Flat sheet	2%	[31]
		Thin film composite with aromaticpolyamide coated with an ultrathin polyimide		NF		ESNA	Flat sheet	39%	[31]
	Estriol	Thin film composite with aromaticpolyamide coated with an ultrathin polyimide	2–<150 ng/L-surface water	NF		ESNA	Flat sheet	32%	[31]
		–	108 ng/L Effluent from a WWTP	UF	–	–	–	40.7%	[32]
		–	128 ng/L Saline ground water	RO	–	–	–	80.5%<	[32]
	Estrone	Aromatic polyamide	5–18 μg/L surface water	NF	1 nm	NF-90	Flat sheet	93%	[30]
				NF	1.3 nm	NF-200	Flat sheet	81%	[30]
		Thin film composite with sulfonated polyethersulfone coated with an ultrathin polyimide	2–<150 ng/L surface water	UF		GM	Flat sheet	45%	[31]
		Thin film composite with aromaticpolyamide coated with an ultrathin polyimide		NF		ESNA	Flat sheet	41%	[31]
		–	98 ng/L Effluent from a WWTP	UF	–	–	–	90.8%	[32]
		–	83, 167 ng/L Saline ground water	RO	–	–	–	85%<	[32]
	Ethinylestradiol	Thin film composite with sulfonated polyethersulfone coated with an ultrathin polyimide	2–<150 ng/L surface water	UF		GM	Flat sheet	33%	[31]
		Thin film composite with aromaticpolyamide coated with an ultrathin polyimide		NF		ESNA	Flat sheet	59%	[31]
		–	78 ng/L Effluent from a WWTP	UF	–	–	–	98.7%	[32]
		–	51, 125 ng/L Saline ground water	RO	–	–	–	80%<	[32]
	Progesterone	Thin film composite with sulfonated polyethersulfone coated with an ultrathin polyimide	2–<150 ng/L surface water	UF		GM	Flat sheet	55%	[31]
				NF		ESNA	Flat sheet	66%	[31]

(*Continued*)

Table 2 (*Continued*)

Therapeutic class	Removed pharmaceuticals, hormones, endocrine disruptors, and their metabolites	Membrane material	Initial concentration-source	Filtration type	Effective pore size	Commercial code	Configuration	Removal efficiency range	Refs.
		Thin film composite with aromaticpolyamide coated with an ultrathin polyimide							
		–	64 ng/L Effluent from a WWTP	UF	–	–	–	98.4%<	[32]
		–	250, 285 ng/L-Saline groundwater	RO	–	–	–	91.2%<	[32]
	Testosterone	Thin film composite with sulfonated polyethersulfone coated with an ultrathin polyimide	2–<150 ng/L surface water	UF		GM	Flat sheet	31%	[31]
		Thin film composite with aromaticpolyamide coated with an ultrathin polyimide		NF		ESNA	Flat sheet	62%	[31]
		–	81 ng/L-Effluent from a WWTP	UF	–	–	–	71.6%	[32]
Organic solvents	Dioxane	Aromatic polyamide	5–18 μg/L surface water	NF	1 nm	NF-90	Flat sheet	46%	[30]

Table 3
An overview of MBRs used for the removal of pharmaceuticals, hormones, endocrine disruptors, and their metabolites

Therapeutic class	Removed pharmaceuticals, hormones, endocrine disruptors, and their metabolites	Reactor type	Initial concentration-source	Membrane configuration	HRT	Removal details	Refs.
Analgesics, anti-inflammatories, and antipyretics	Acetaminophen	ELA MBR	1000 mg/L	Flat sheet	–	100% (SRT: 1 d)	[46]
		Submerged	50 μg/L effluent of a STP	Hollow fiber	9, 13 h	100% (SRT: 15 and 30 d)	[11]
		Submerged	0.97 μg/L synthetic	Flat sheet	6 h	89–90% (SRT: 8, 20, and 80 d)	[49]
		–	100 μg/L model of a WWTP effluent	Flat sheet	5 d	>99.9%	[50]
		Submerged	18 μg/L effluent of a WWTP	Flat sheet	–	Average removal efficiency: 99.6% (The SRT was infinite.)	[51]
		Side-stream	9.9 μg/L effluent of a WWTP	Flat sheet	15 h	Average removal efficiency: 99.8% (at prolonged SRT)	[52]
		Side-stream	9.9 μg/L effluent of a WWTP	Hollow fiber	7.2 h	Average removal efficiency: 99.9% (at prolonged SRT)	[52]
	Codeine	Side-stream	247 ng/L effluent of a STP	Hollow fiber	2.5, 5, 24 h	>93%	[53]
	Diclofenac	Submerged	0.91 μg/L synthetic	Flat sheet	6 h	15–33% (SRT: 8, 20, and 80 d)	[49]
		Submerged	2.8 μg/L effluent of a WWTP	Flat sheet	–	Average removal efficiency: 87.4% (The SRT was infinite.)	[51]
		Side-stream	1.32 μg/L effluent of a WWTP	Flat sheet	15 h	Average removal efficiency: 65.8% (at prolonged SRT)	[52]
		Side-stream	1.32–9.9 μg/L effluent of a WWTP	Hollow fiber	7.2 h	Average removal efficiency: 62.6% (at prolonged SRT)	[52]
		Side-stream	663 ng/L effluent of a STP	Hollow fiber	2.5, 5, 24 h	86%	[53]
		Side-stream	10 mg/L model of a domestic sewage	Hollow fiber	24 h	It could not be removed. (SRT: 72 d)	[54]
		Submerged	100 μg/L synthetic	Hollow fiber	24 h	14–98%	[55]
		Side-stream	4526 ng/L model of a municipal wastewater	Tubular	26 h	Average removal efficiency: 27% (SRT: 88 d)	[56]
		–	3190 ng/L effluent of a WWTP	–	24 h	(<20%)<removal<60% (SRT: 1, 5, 13 and approx. 26 d)	[57]
		Submerged	2083 μg/L effluent of a WWTP	Flat sheet	7, 10 h	Average removal efficiency: 58%	[58]
		–	1000 ng/L effluent of a WWTP	–	13 h	15–35% (SRT: 16–75 d)	[59]
		Side-stream	10 μg/L synthetic	Flat sheet	–	51–90%<% (SRT increased with time of operation (286 d))	[60]
		Submerged	50 ng/L effluent of a WWTP	Hollow fiber	9 h	21%	[61]
		Side-stream	3250, 4114, 3190 ng/L effluent of a WWTP	–	12, 28.8, 96 h	0–50% (SRT: 10–55 d)	[62]
	2,4-Dichlorobenzoic acid	Submerged	455 μg/L effluent of a WWTP	Flat sheet	7, 10 h	Average removal efficiency: 83%	[58]
	etodolac	Submerged	Pharmaceutical process wastewater	Flat sheet	24 h	25.8–81.1% (SRT: 15 and 30 d)	[12]
	Fenoprofen	Submerged	0.81 μg/L synthetic	Flat sheet	6 h	81–90% (SRT: 8, 20, and 80 d)	[49]

Therapeutic class	Removed pharmaceuticals, hormones, endocrine disruptors, and their metabolites	Reactor type	Initial concentration-source	Membrane configuration	HRT	Removal details	Refs.
		Submerged	100 μg/L synthetic	Hollow fiber	24 h	22–99%	[55]
	Ibuprofen	Submerged	1.02 μg/L synthetic	Flat sheet	6 h	80%<removal<100% (SRT: 8, 20, and 80 d)	[49]
		Submerged	17.5 μg/L effluent of a WWTP	Flat sheet	–	Average removal efficiency: 99.8% (The SRT was infinite.)	[51]
		Side-stream	21.7 μg/L effluent of a WWTP	Flat sheet	15 h	Average removal efficiency: 99.2% (at prolonged SRT)	[52]
		Side-stream	21.7 μg/L effluent of a WWTP	Hollow fiber	7.2 h	Average removal efficiency: 99.5% (at prolonged SRT)	[52]
		Side-stream	158 ng/L effluent of a STP	Hollow fiber	2.5, 5, 24 h	>95%	[53]
		Submerged	10 mg/L model of a domestic sewage	Hollow fiber	24 h	98% (SRT: 72 d)	[54]
		Submerged	100 μg/L synthetic	Hollow fiber	24 h	34–100%	[55]
		Side-stream	2595 ng/L model of a municipal wastewater	Tubular	26 h	Average removal efficiency: 99% (SRT: 88 d)	[56]
		–	2448 ng/L effluent of a WWTP	–	24 h	80%<removal<100% (SRT: 1, 5, 13 and approx. 26 d)	[57]
		Submerged	6725 μg/L effluent of a WWTP	Flat sheet	7, 10 h	Average removal efficiency: 99%	[58]
		–	1100 ng/L effluent of a WWTP	–	13 h	90–95% (SRT: 16–75 d)	[59]
		Side-stream	10 μg/L synthetic	Flat sheet	–	51–90%<% (SRT increased with time of operation (286 d))	[60]
		Submerged	470 ng/L effluent of a WWTP	Hollow fiber	9 h	96%	[61]
		Side-stream	1480, 2679, 2448 ng/L effluent of a WWTP	–	12, 28.8, 96 h	97–99% (SRT: 10–55 d)	[62]
	Indomethacin	Submerged	0.15 μg/L effluent of a WWTP	Flat sheet	–	Average removal efficiency: 46.6% (The SRT was infinite.)	[51]
		Side-stream	0.875 μg/L effluent of a WWTP	Flat sheet	15 h	Average removal efficiency: 41.4% (At prolonged SRT)	[52]
		Side-stream	0.875 μg/L effluent of a WWTP	Hollow fiber	7.2 h	Average removal efficiency: 39.7% (At prolonged SRT)	[52]
		Submerged	100 μg/L synthetic	Hollow fiber	24 h	36–90%	[55]
	Ketoprofen	Submerged	50 μg/L effluent of a STP	Hollow fiber	9, 13 h	100% (SRT: 15 and 30 d)	[11]
		Submerged	1.07 μg/L synthetic	Flat sheet	6 h	60–91% (SRT: 8, 20, and 80 d)	[49]
		Submerged	1.8 μg/L effluent of a WWTP	Flat sheet	–	Average removal efficiency: 91.9% (The SRT was infinite.)	[51]
		Side-stream	1.08 μg/L effluent of a WWTP	Flat sheet	15 h	Average removal efficiency: 43.9% (At prolonged SRT)	[52]
		Side-stream	1.08 μg/L effluent of a WWTP	Hollow fiber	7.2 h	Average removal efficiency: 44% (At prolonged SRT)	[52]

(*Continued*)

Table 3 *(Continued)*

Therapeutic class	Removed pharmaceuticals, hormones, endocrine disruptors, and their metabolites	Reactor type	Initial concentration-source	Membrane configuration	HRT	Removal details	Refs.
	Submerged	310 ng/L effluent of a WWTP	Hollow fiber	9 h	94%	[61]	
	Mefenamic acid	Submerged	25 ng/L effluent of a WWTP	Flat sheet	–	Average removal efficiency: 74.8% (The SRT was infinite.)	[51]
		Side-stream	1.07 μg/L effluent of a WWTP	Flat sheet	15 h	Average removal efficiency: 40.5% (At prolonged SRT)	[52]
		Side-stream	1.07 μg/L effluent of a WWTP	Hollow fiber	7.2 h	Average removal efficiency: 35.5% (At prolonged SRT)	[52]
		Submerged	70 ng/L effluent of a WWTP	Hollow fiber	9 h	76%	[61]
	Naproxen	Submerged	50 μg/L effluent of a STP	Hollow fiber	9, 13 h	60–100% (SRT: 15 and 30 d)	[11]
		Submerged	0.8 μg/L synthetic	Flat sheet	6 h	18–26% (SRT: 8, 20, and 80 d)	[49]
		Submerged	11.5 μg/L effluent of a WWTP	Flat sheet	–	Average removal efficiency: 99.3% (The SRT was infinite.)	[51]
		Side-stream	0.463 μg/L effluent of a WWTP	Flat sheet	15 h	Average removal efficiency: 90.7% (At prolonged SRT)	[52]
		Side-stream	0.463 μg/L effluent of a WWTP	Hollow fiber	7.2 h	Average removal efficiency: 91.6% (At prolonged SRT)	[52]
		Side-stream	278 ng/L effluent of a STP	Hollow fiber	2.5, 5, 24 h	>95%	[53]
		Submerged	10 mg/L model of a domestic sewage	Hollow fiber	24 h	84% (SRT: 72 d)	[54]
		Submerged	100 μg/L synthetic	Hollow fiber	24 h	–2–75% (SRT: 72 d)	[55]
		Side-stream	3780 ng/L model of a municipal wastewater	Tubular	26 h	Average removal efficiency: 82% (SRT: 88 d)	[56]
		–	1050 ng/L effluent of a WWTP	–	13 h	73–82% (SRT: 16–75 d)	[59]
		Side-stream	10 μg/L synthetic	Flat sheet	–	51–90%<% (SRT increased with time of operation (286 d))	[60]
		Submerged	140 ng/L effluent of a WWTP	Hollow fiber	9 h	85%	[61]
		Submerged	0.5–2 μg/L municipal wastewater	Flat sheet	81.6, 151.2 h	About 60% (SRT>100 d)	[63]
	Phenacetine	Submerged	1.2 μg/L synthetic	Flat sheet	6 h	86–91.7% (SRT: 8, 20, and 80 d)	[49]
	Propyphenazone	Submerged	62 ng/L effluent of a WWTP	Flat sheet	–	Average removal efficiency: 64.6% (The SRT was infinite.)	[51]
		Side-stream	0.065 μg/L effluent of a WWTP	Flat sheet	15 h	Average removal efficiency: 64.5% (At prolonged SRT)	[52]
		Side-stream	0.065 μg/L effluent of a WWTP	Hollow fiber	7.2 h	Average removal efficiency: 60.7% (At prolonged SRT)	[52]
		Submerged	100 μg/L synthetic	Hollow fiber	24 h	5–16%	[55]
	Salicylic acid	Side-stream	3400 ng/L model of a municipal wastewater	Tubular	26 h	Average removal efficiency: 89% (SRT: 88 d)	[56]

Therapeutic class	Removed pharmaceuticals, hormones, endocrine disruptors, and their metabolites	Reactor type	Initial concentration-source	Membrane configuration	HRT	Removal details	Refs.
Antibiotics	Clarithromycin	Side-stream	259 ng/L effluent of a STP	Hollow fiber	2.5, 5, 24 h	75%	[53]
	Erythromycin	Submerged	150 ng/L effluent of a WWTP	Flat sheet	–	Average removal efficiency: 67.3% (The SRT was infinite.)	[51]
		Side-stream	0.82 μg/L effluent of a WWTP	Flat sheet	15 h	Average removal efficiency: 43.0% (At prolonged SRT)	[52]
		Side-stream	0.82 μg/L effluent of a WWTP	Hollow fiber	7.2 h	Average removal efficiency: 25.2% (At prolonged SRT)	[52]
		Submerged	10 mg/L model of a domestic sewage	Hollow fiber	24 h	91% (SRT: 72 d)	[54]
		Side-stream	10 μg/L synthetic	Flat sheet	–	71%-almost complete removal (SRT increased with time of operation (286 d))	[60]
	Metronidazole	Side-stream	392 ng/L model of a municipal wastewater	Tubular	26 h	Average removal efficiency: 80% (SRT: 88 d)	[56]
	N4-acetyl-sulfamethoxazole	–	90 ng/L effluent of a STP	–	2.5, 5, 24 h	92%	[53]
		–	1000 ng/L effluent of a WWTP	–	13 h	70–92% (SRT: 16–75 d)	[59]
	Ofloxacin	Submerged	450 ng/L effluent of a WWTP	Flat sheet	–	Average removal efficiency: 94.4% (The SRT was infinite.)	[51]
		Side-stream	10.5 μg/L effluent of a WWTP	Flat sheet	15 h	Average removal efficiency: 95.2% (At prolonged SRT)	[52]
		Side-stream	10.5 μg/L effluent of a WWTP	Hollow fiber	7.2 h	Average removal efficiency: 91.3% (At prolonged SRT)	[52]
	Roxithromycin	Submerged	50 μg/L effluent of a STP	Hollow fiber	9, 13 h	5–85% (SRT: 15 and 30 d)	[11]
		Submerged	10 mg/L model of a domestic sewage	Hollow fiber	24 h	77% (SRT: 72 d)	[54]
		–	300 ng/L effluent of a WWTP	–	13 h	36–60% (SRT: 16–75 d)	[59]
		Side-stream	10 μg/L synthetic	Flat sheet	–	71%-almost complete removal (SRT increased with time of operation (286 d))	[60]
		Side-stream	26, 64, 117 ng/L effluent of a WWTP	–	12, 28.8, 96 h	34–100% (SRT: 10–55 d)	[62]
	Sulfamethoxazole	Submerged	50 μg/L effluent of a STP	Hollow fiber	9, 13 h	30–90% (SRT: 15 and 30 d)	[11]
		Submerged	800 ng/L effluent of a WWTP	Flat sheet	–	Average removal efficiency: 60.5% (The SRT was infinite.)	[51]
		Side-stream	0.093 μg/L effluent of a WWTP	Flat sheet	15 h	Average removal efficiency: 80.8% (At prolonged SRT)	[52]
		Side-stream	0.093 μg/L effluent of a WWTP	Hollow fiber	7.2 h	Average removal efficiency: 78.3% (At prolonged SRT)	[52]
		Side-stream	259 ng/L effluent of a STP	Hollow fiber	2.5, 5, 24 h	52%	[53]
		Submerged	10 mg/L model of a domestic sewage	Hollow fiber	24 h	52% (SRT: 72 d)	[54]
		–	1350 ng/L effluent of a WWTP	–	13 h	No removal was observed.	[59]
		Side-stream	145 ng/L effluent of a WWTP	–	12, 28.8, 96 h	61% (SRT: 10–55 d)	[62]

Table 3 *(Continued)*

Therapeutic class	Removed pharmaceuticals, hormones, endocrine disruptors, and their metabolites	Reactor type	Initial concentration-source	Membrane configuration	HRT	Removal details	Refs.
	Trimethoprim	Submerged	50 μg/L effluent of a STP	Hollow fiber	9, 13 h	60–100% (SRT: 15 and 30 d)	[11]
		Side-stream	0.204 μg/L effluent of a WWTP	Flat sheet	15 h	Average removal efficiency: 66.7% (At prolonged SRT)	[52]
		Side-stream	0.204 μg/L effluent of a WWTP	Hollow fiber	7.2 h	Average removal efficiency: 47.5% (At prolonged SRT)	[52]
		Submerged	10 mg/L model of a domestic sewage	Hollow fiber	24 h	36% (SRT: 72 d)	[54]
		Side-stream	10 μg/L synthetic	Flat sheet	–	No removal occurred in first steps, but it was almost completely removed in last step (SRT increased with time of operation (286 d)).	[60]
Antidepressants	Amitriptyline	Side-stream	1732 ng/L model of a municipal wastewater	Tubular	26 h	Average removal efficiency: 97% (SRT: 88 ds)	[56]
	Fluoxetine	–	0.573 μg/L effluent of a WWTP	Flat sheet	15 h	Average removal efficiency: 98% (At prolonged SRT)	[52]
		–	0.573 μg/L effluent of a WWTP	Hollow fiber	7.2 h	Average removal efficiency: 98% (At prolonged SRT)	[52]
		Side-stream	20 μg/L synthetic	Flat sheet	–	82–98% (SRT increased with time of operation (286 d))	[60]
	Paroxetine	Submerged	38 ng/L effluent of a WWTP	Flat sheet	–	Average removal efficiency: 89.7% (The SRT was infinite.)	[51]
Antidiabetics	Glibenclamide	Submerged	57 ng/L effluent of a WWTP	Flat sheet	–	Average removal efficiency: 47.3% (The SRT was infinite.)	[51]
		Side-stream	9.89 μg/L effluent of a WWTP	Flat sheet	15 h	Average removal efficiency: 95.6% (At prolonged SRT)	[52]
		Side-stream	9.89 μg/L effluent of a WWTP	Hollow fiber	7.2 h	Average removal efficiency: 82.2% (At prolonged SRT)	[52]
Antiepileptics	Carbamazepine	Submerged	1.13 μg/L synthetic	Flat sheet	6 h	4–8% (SRT: 8, 20, and 80 d)	[49]
		Submerged	240 ng/L effluent of a WWTP	Flat sheet	–	No elimination (The SRT was infinite.)	[51]
		Side-stream	0.156 μg/L effluent of a WWTP	Flat sheet	15 h	No elimination (At prolonged SRT)	[52]
		Side-stream	0.156 μg/L effluent of a WWTP	Hollow fiber	7.2 h	No elimination (At prolonged SRT)	[52]

(*Continued*)

Therapeutic class	Removed pharmaceuticals, hormones, endocrine disruptors, and their metabolites	Reactor type	Initial concentration-source	Membrane configuration	HRT	Removal details	Refs.
		–	704 ng/L effluent of a WWTP	–	24 h	Removal<20% (SRT: 1, 5, 13 and approx. 26 d)	[57]
		Submerged	1287 μg/L effluent of a WWTP	Flat sheet	7, 10 h	Average removal efficiency: 13%	[58]
		–	1000 ng/L effluent of a WWTP	–	13 h	0–25% (SRT: 16–75 d)	[59]
		Side-stream	20 μg/L synthetic	Flat sheet	–	<20–90% (SRT increased with time of operation (286 d))	[60]
		Side-stream	1850, 1200, 704 ng/L effluent of a WWTP	–	12, 28.8, 96 h	0–12%	[62]
	Primidone	Submerged	0.5–2 μg/L municipal wastewater	Flat sheet	81.6, 151.2 h	About 60% (SRT>100 d)	[63]
Antihistamins	Loratadine	Side-stream	0.028 μg/L effluent of a WWTP	Flat sheet	15 h	No elimination	[52]
		Side-stream	0.028 μg/L effluent of a WWTP	Hollow fiber	7.2 h	Average removal efficiency: 33.5%	[52]
Anxiolytic sedatives hypnotics and antipsychotics	Diazepam	Submerged	20 mg/L model of a domestic sewage	Hollow fiber	24 h	26% (SRT: 72 d)	[54]
		Side-stream	20 μg/L synthetic	Flat sheet	–	<20–90% (SRT increased with time of operation (286 d))	[60]
Bronchodilators and anti-asthma Drugs	Caffeine	Submerged	0.87 μg/L synthetic	Flat sheet	6 h	82.7–88.5% (SRT: 8, 20, and 80 d)	[49]
Cardiovascular drugs	Atenolol	Submerged	1.5 μg/L effluent of a WWTP	Flat sheet	–	Average removal efficiency: 65.5% (The SRT was infinite.)	[51]
		Side-stream	2 μg/L effluent of a WWTP	Flat sheet	15 h	Average removal efficiency: 76.7% (At prolonged SRT)	[52]
		Side-stream	2 μg/L effluent of a WWTP	Hollow fiber	7.2 h	Average removal efficiency: 69.5% (At prolonged SRT)	[52]
	Bezafibrate	Submerged	1.27 μg/L synthetic	Flat sheet	6 h	86–92% (SRT: 8, 20, and 80 d)	[49]
		Submerged	1.75 μg/L effluent of a WWTP	Flat sheet	–	Average removal efficiency: 95.8% (The SRT was infinite.)	[51]
		Side-stream	14.9 μg/L effluent of a WWTP	Flat sheet	15 h	Average removal efficiency: 90.3% (At prolonged SRT)	[52]
		Side-stream	14.9 μg/L effluent of a WWTP	Hollow fiber	7.2 h	Average removal efficiency: 88.2% (At prolonged SRT)	[52]
		–	6840 ng/L effluent of a WWTP	–	24 h	60%<removal<100% (SRT: 1, 5, 13 and approx. 26 d)	[57]
		Side-stream	1960, 2014, 6840 ng/L effluent of a WWTP	–	12, 28.8, 96 h	77–96% (SRT: 10–55 d)	[62]
	Clofibric acid	Submerged	0.79 μg/L synthetic	Flat sheet	6 h	4–34% (SRT: 8, 20, and 80 d)	[49]
		Submerged	110 ng/L effluent of a WWTP	Flat sheet	–	Average removal efficiency: 71.8% (The SRT was infinite.)	[51]

Therapeutic class	Removed pharmaceuticals, hormones, endocrine disruptors, and their metabolites	Reactor type	Initial concentration-source	Membrane configuration	HRT	Removal details	Refs.
		Submerged	100 μg/L synthetic	Hollow fiber	24 h	–2–40%	[55]
		Side-stream	2475 ng/L model of a municipal wastewater	Tubular	26 h	Average removal efficiency: 82% (SRT: 88 d)	[56]
		Submerged	92 μg/L effluent of a WWTP	Flat sheet	7, 10 h	Average removal efficiency: 54%	[58]
		Submerged	35 ng/L effluent of a WWTP	Hollow fiber	9 h	85%	[61]
		Submerged	0.5–2 μg/L municipal wastewater	Flat sheet	81.6, 151.2 h	About 60% (SRT>100 d)	[63]
	Gemfibrozil	Submerged	0.83 μg/L synthetic	Flat sheet	6 h	31–88% (SRT: 8, 20, and 80 d)	[49]
		Submerged	3.8 μg/L effluent of a WWTP	Flat sheet	–	Average removal efficiency: 89.6% (The SRT was infinite.)	[51]
		Side-stream	3.08 μg/L effluent of a WWTP	Flat sheet	15 h	Average removal efficiency: 42.2% (At prolonged SRT)	[52]
		Side-stream	3.08 μg/L effluent of a WWTP	Hollow fiber	7.2 h	Average removal efficiency: 32.5% (At prolonged SRT)	[52]
		Submerged	100 μg/L synthetic	Hollow fiber	24 h	–20–98%	[55]
		Side-stream	2376 ng/L model of a municipal wastewater	Tubular	26 h	Average removal efficiency: 97% (SRT: 88 d)	[56]
	Hydrochlorothiazide	Submerged	6.4 μg/L effluent of a WWTP	Flat sheet	–	Average removal efficiency: 66.3% (The SRT was infinite.)	[51]
		Side-stream	2.74 μg/L effluent of a WWTP	Flat sheet	15 h	No elimination (At prolonged SRT)	[52]
		Side-stream	2.74 μg/L effluent of a WWTP	Hollow fiber	7.2 h	No elimination (At prolonged SRT)	[52]
	Metoprolol	Submerged	350 ng/L effluent of a WWTP	Flat sheet	–	Average removal efficiency: 58.7% (The SRT was infinite.)	[51]
		Side-stream	0.039 μg/L effluent of a WWTP	Flat sheet	15 h	Average removal efficiency: 44.2% (At prolonged SRT)	[52]
		Side-stream	0.039 μg/L effluent of a WWTP	Hollow fiber	7.2 h	Average removal efficiency: 29.5% (At prolonged SRT)	[52]
	Pentoxifylline	Submerged	1.04 μg/L synthetic	Flat sheet	6 h	33–91% (SRT: 8, 20, and 80 d)	[49]
	Pravastatin	Submerged	230 ng/L effluent of a WWTP	Flat sheet	–	Average removal efficiency: 90.8% (The SRT was infinite.)	[51]
		Side-stream	0.886 μg/L effluent of a WWTP	Flat sheet	15 h	Average removal efficiency: 86.1% (At prolonged SRT)	[52]
		Side-stream	0.886 μg/L effluent of a WWTP	Hollow fiber	7.2 h	Average removal efficiency: 83.1% (At prolonged SRT)	[52]
	Propranolol	Side-stream	0.292 μg/L effluent of a WWTP	Flat sheet	15 h		[52]

(*Continued*)

Therapeutic class	Removed pharmaceuticals, hormones, endocrine disruptors, and their metabolites	Reactor type	Initial concentration-source	Membrane configuration	HRT	Removal details	Refs.
Endocrine disruptors	Benzophenone	Submerged	100 μg/L synthetic	Hollow fiber	24 h	61–80%	[55]
		Side-stream	3025 ng/L model of a municipal wastewater	Tubular	26 h	Average removal efficiency: 98% (SRT: 88 d)	[56]
	Bisphenol A	Submerged	100 μg/L synthetic	Hollow fiber	24 h	54–99%	[55]
			2151 ng/L effluent of a WWTP	–	24 h	80%<removal<100% (SRT: 1, 5, 13 and approx. 26 d)	[57]
		Side-stream	2025, 2376, 2151 ng/L effluent of a WWTP	–	12, 28.8, 96 h	93–99% (SRT: 10–55 d)	[62]
	Nonylphenol	Side-stream	4031, 2673, 3129 ng/L effluent of a WWTP	–	12, 28.8, 96 h	85–91% (SRT: 10–55 d)	[62]
	Nonylphenol monoethoxylate	Side-stream	7116, 7299, 4450 ng/L effluent of a WWTP	–	12, 28.8, 96 h	97–99% (SRT: 10–55 d)	[62]
	Nonylphenol diethoxylate	Side-stream	866, 767, 835 ng/L effluent of a WWTP	–	12, 28.8, 96 h	85–94% (SRT: 10–55 d)	[62]
	Nonylphenoxyacetic acid	Side-stream	724, 737, 429 ng/L effluent of a WWTP	–	12, 28.8, 96 h	No elimination (SRT: 10–55 d)	[62]
			Nonylphenoxyethoxyacetic acid	Side-stream	362, 107, 471 ng/L effluent of a WWTP	–	12, 28.8, 96 h
	No elimination (SRT: 10–55 d)	[62]					
	Octylphenol	Side-stream	118, 436, 215 ng/L effluent of a WWTP	–	12, 28.8, 96 h	45–100% (SRT: 10–55 d)	[62]
	Octylphenol monoethoxylate	Side-stream	213, 552, 42 ng/L effluent of a WWTP	–	12, 28.8, 96 h	91–100% (SRT: 10–55 d)	[62]
Octylphenol diethoxylate	Side-stream	36, 55 ng/L effluent of a WWTP	–	12, 28.8, 96 h	58–100% (SRT: 10–55 d)	[62]	
Gastrointestinal drugs	Famotidine	Side-stream	0.08 μg/L effluent of a WWTP	Flat sheet	15 h	Average removal efficiency: 64.6% (At prolonged SRT)	[52]
		Side-stream	0.08 μg/L effluent of a WWTP	Hollow fiber	7.2 h	Average removal efficiency: 47.4% (At prolonged SRT)	[52]
	Ranitidine	Submerged	300 ng/L effluent of a WWTP	Flat sheet	–	Average removal efficiency: 95.0% (The SRT was infinite.)	[51]
		Side-stream	0.347 μg/L effluent of a WWTP	Flat sheet	15 h	Average removal efficiency: 44.2% (At prolonged SRT)	[52]
		Side-stream	0.347 μg/L effluent of a WWTP	Hollow fiber	7.2 h	Average removal efficiency: 29.5% (At prolonged SRT)	[52]
Hormones, their modulators and estrogens	17-ethinyl-estradiol	Submerged	0.7 μg/L synthetic	Flat sheet	6 h	39–78% (SRT: 8, 20, and 80 d)	[49]
		Submerged	100 μg/L synthetic	Hollow fiber	24 h	61–71%	[55]
		Side-stream	1540 ng/L model of a municipal wastewater	Tubular	26 h	Average removal efficiency: 95% (SRT: 88 d)	[56]
		–	3 ng/L effluent of a WWTP	–	24 h	20%<removal<100% (SRT: 1, 5, 13 and approx. 26 d)	[57]
		Submerged	83 ng/L model of a effluent of a WWTP	Flat sheet	9.6, 24, 48, 96 h	Average removal efficiency: 18.3–>99%	[64]

Therapeutic class	Removed pharmaceuticals, hormones, endocrine disruptors, and their metabolites	Reactor type	Initial concentration-source	Membrane configuration	HRT	Removal details	Refs.
	17ß-estradiol	Submerged	0.93 μg/L synthetic	Flat sheet	6 h	98–100% (SRT: 8, 20, and 80 d)	[49]
		Submerged	100 μg/L synthetic	Hollow fiber	24 h	99–100%	[55]
		Side-stream	1920 ng/L model of a municipal wastewater	Tubular	26 h	Average removal efficiency: 100% (SRT: 88 d)	[56]
	17 ß-Estrodiol-17-acetate	Side-stream	1661 ng/L model of a municipal wastewater	Tubular	26 h	Average removal efficiency: 98% (SRT: 88 d)	[56]
	Estriol	Side-stream	1720 ng/L model of a municipal wastewater	Tubular	26 h	Average removal efficiency: 96% (SRT: 88 d)	[56]
	Estrone	Submerged	0.97 μg/L synthetic	Flat sheet	6 h	98–100% (SRT: 8, 20, and 80 d)	[49]
		Side-stream	1608 ng/L model of a municipal wastewater	Tubular	26 h	Average removal efficiency: 97% (SRT: 88 d)	[56]
	Bethametasone dipropionate	Submerged	99.45 μg/L wastewater of a pharmaceutical company	Hollow fiber	24 h	Average removal efficiency: 99.6% (SRT: 30 d)	[65]
	Bethametasone valerate	Submerged	99 μg/L wastewater of a pharmaceutical company	Hollow fiber	24 h	Average removal efficiency: 97.8% (SRT: 30 d)	[65]
	Levonogestrel	Submerged	109.05 μg/L wastewater of a pharmaceutical company	Hollow fiber	24 h	Average removal efficiency: 98.7% (SRT: 30 d)	[65]
	Medroxyprogesterone acetate	Submerged	105.2 μg/L-wastewater of a pharmaceutical company	Hollow fiber	24 h	Average removal efficiency: 93.4% (SRT: 30 d)	[65]

(11) Many of the investigated membranes have been made of polyamide.

In several studies, size exclusion has been considered as an influential factor affecting the removal of pharmaceuticals [29,33,37,39].

3. Membrane bioreactors

MBRs have been increasingly used for wastewater treatment applications. MBRs combine biological and membrane treatment for effective removal of contaminants from wastewaters. They are similar to CASs with the exception that the biomass responsible for removing the contaminants is retained within the bioreactor component of the system using membranes rather than secondary clarifiers [44]. Conventional treatment of municipal wastewater usually proceeds through a three stage process: sedimentation of gross solids in the feed water followed by aerobic degradation of the organic matter and then a second sedimentation process to remove the biomass. An MBR can displace the physical separation process by filtering the biomass through a membrane. As a result, the product water quality is significantly higher than that generated by conventional treatment, since it eliminates the need for a further tertiary disinfection process [45]. In fact, MBR technology offers several advantages over CAS plants such as operation at high biomass concentrations, reduced excess sludge production, extremely low suspended solid concentrations in the treated effluent, drastically enhanced elimination of pathogens and viruses [10]. It is also worth to mention that MBR makes hydraulic retention time independent from sludge retention time [46].

The basic schematic diagram of MBR configuration is shown in Fig. 1. Fig. 1(a) displays an immersed or submerged membrane bioreactor module while a side-stream or external membrane module is illustrated in Fig. 1(b) [47].

External membrane systems usually operate at a constant pressure and variable permeate flux (i.e. permeate flux decreases as membrane fouls); on the other hand, submerged membranes typically operate at a constant flow and variable transmembrane pressure (i.e. transmembrane pressure increases as membrane fouls) [44].

For side-stream MBR systems, the feed wastewater is directly in contact with biomass. Wastewater and biomass are both pumped through the recirculation loop consisted of membranes. The concentrated sludge is recycled back to the reactor while the water effluent is discharged [48]. The idea of separating the membrane and bioreactor is to ease the membrane maintenance but it will increase the operational cost due to recirculation loop installation. The submerged system has less operational cost because there is no recirculation loop compared to the external system and a biological process occurs around the membrane in submerged MBR. Both submerged and external MBRs need to pump out the excess sludge to maintain sludge age. The mode of membrane transportation could be pressure driven or vacuum driven. Pressure-driven filtration is used in side-stream MBR and vacuum driven is used for submerged MBR [47].

MBRs hold a promise for the degradation of micro-pollutants, which could be ascribed especially to the high sludge concentration and relatively high sludge age at which they operate. This makes the presence of microorganisms that are capable of degrading the specific micro-pollutants more likely [10]. Regarding this fact, several papers have investigated the removal of pharmaceutical and personal care products (PPCPs), hormones, endocrine disruptors, and their metabolites. Table 1 is an overview of these papers which summarizes the removed pollutant, reactor type, membrane configuration, and the obtained removal efficiencies.

According to Table 3, the following results can be obtained:

(1) Hollow fiber and flat sheet have been used frequently. Tubular have been used only in one study.
(2) Both side-stream and submerged MBRs have been widely used.
(3) Acetaminophen could successfully get removed by MBRs. In fact, five studies have proposed conditions in which more than 99% of this pollutant has been removed. This indicates the perfect performance of these systems in the removal of acetaminophen.
(4) For diclofenac, there have been cases in which no elimination occurred; however, removal efficiencies of about 60% could be obtained at prolonged SRTs.
(5) The removal of ibuprofen has been investigated by flat sheet, hollow fiber, and tubular configurations. As it can be seen in Table 2, the results have been significant.
(6) The removal of only seven antibiotics has been studied by MBRs. However, Verlicchi et al. have detected thirty-six antibiotics in raw urban wastewater and effluent from an activated sludge system [2].
(7) More than 99% of ofloxacin has been removed at prolonged SRTs, which has been the best efficiency among the antibiotics.

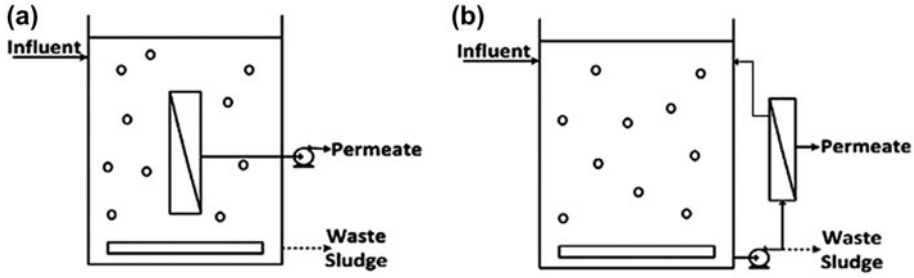

Fig. 1. The basic schematic diagram of MBR configuration: (a) submerged and (b) side-stream [47].

(8) The removal of carbamazepine by MBRs has not been satisfactory. In most of the cases, the removal efficiency has been less than 30%.
(9) MBRs have shown great performance in the removal of the studied hormones and estrogens.

The MBRs performances can be affected by membrane material, module configuration, membrane operating conditions (transmembrane pressure, backwash, etc.), biological operating conditions (temperature, SRT), and characteristics of activated sludge [66]. The SRT has been regarded as one of the most important parameters affecting the biodegradation of micro-pollutants such as pharmaceuticals [10].

The positive effect of increasing SRT appears for several compounds, in particular for hormones, ibuprofen, ketoprofen, naproxen, bezafibrate, gemfibrozil, fluoxetine, and antibiotics. On the other hand, increasing SRT beyond 30 d does not usually result in a consistent increment in the removal of most of the compounds [2]. Maeng et al. [49] reported that removal efficiencies of gemfibrozil, ketoprofen, clofibric acid, and 17-ethinylestradiol were increased when SRT was increased from 20 to 80 d. Moreover, MBR operated at a short SRT (8 d) was able to effectively remove hydrophilic-neutral pharmaceuticals (phenacetin, acetaminophen, pentoxifylline, and caffeine), hydrophilic-ionic pharmaceuticals (bezafibrate, ibuprofen, and fenoprofen), and estrogens (17ß-estradiol and estrone).

For etodolac, as the SRT increased from 15 to 30 d, the overall removal efficiencies improved [12]. Tambosi et al. [11] evaluated the treatment of wastewater containing three NSAIDs (acetaminophen, ketoprofen, and naproxen) and three antibiotics (roxithromycin, sulfamethoxazole, and trimethoprim) in two MBRs at SRTs of 15 and 30 d. For all these pharmaceuticals, higher removal efficiencies were obtained as the SRT increased [11].

In another study done by Clara et al. [57], the investigated micropollutants showed different behaviors during the wastewater treatment process. Elimination of some of the compounds was dependent on the solids retention time, whereas carbamazepine was not affected during the treatment. For diclofenac and 17-ethinylestradiole, contradictory results were obtained and beside the SRT other influences seem to be of importance. In another research carried out by Bernhard et al. [58], it was stated that for diclofenac, the removals were 8, 38, and 59% at an SRT of 20, 48, and 62 d, respectively. However, at an SRT of 322 d, the removal efficiency was 53%.

4. Membrane contactors

Membrane contactors are devices that bring two fluids into contact at the entrance of pores. Nowadays, they are most commonly used for producing ultrapure water, wastewater treatments, and water purification, as well as controlling the concentration of several non-volatile solutes in aqueous solutions [67]. Unlike most membrane operations, in membrane contactors, the chemistry of the membrane is relatively unimportant, as it provides no selectivity for the separation process. In fact, the aim is to choose a membrane that causes no negative effects, i.e. that has no negative influence on mass transfer. Therefore, the success of membrane contactors greatly depends on minimizing the membrane resistance to mass transfer [68]. Considering these functionalities, membrane contactors can be used for many separation processes such as liquid–liquid extraction, supported liquid membranes (SLMs), forward osmosis, and membrane distillation.

4.1. Liquid–liquid extraction

In liquid–liquid extraction process, the membrane pores provide an interface between two immiscible fluids. This process involves the transfer of the

Table 4
An overview of membrane processes combined with other processes

Removed pharmaceuticals, hormones, endocrine disruptors, and their metabolites	Process Description	Removal explanation	Refs.
Terbutaline, Salbutamol, Pindolol, Propranolol, Atenolol, Metoprolol, Sotalol, Clenbuterol, Phenazone, Aminopyrine, Carbamazepine, Cyclophosphamide, Pentoxifylline, Ibuprofen, Clofibric acid, Fenoprofen, Gemfibrozil, Ketoprofen, Diclofenac, Bezafibrate	A combination of an NF unit with subsequent granular activated carbon was used	The combination of NF/ granular activated carbon showed the extremely high removal efficiency of >98% for all the pollutants	[33]
Clofibric acid, diclofenac, ibuprofen, ketoprofen, mefenamic acid, naproxen	A combination of coagulation and sedimentation processes with an MBR was used	Clofibric acid and diclofenac were removed with an efficiency of 42% and 21%, respectively. The removal efficiency was >90% for the four others	[61]
Carbamazepine, flumequine, ibuprofen, ofloxacin, and sulfamethoxazole	A combination of nanofiltration (NF) and solar photo-Fenton was used	Using hydrogen peroxide, complete removal of the micropollutants occurred	[78]
Carbamazepine	A laboratory-scale system integrating a membrane bioreactor (MBR) and a TiO_2 slurry photo reactor was used	It could be removed up to 95%	[79]
Ibuprofen	A hybrid photo catalysis–direct contact membrane distillation system was used	Regardless of the process mode, the permeate did not contain ibuprofen	[80]
Sulfamethoxazole, Erythromycin, Trimethoprim, Lincomycin, Ciprofloxacin, Levofloxacin, Tetracycline, Carbamazepine, Primidone, Diclofenac, Triclosan, 17a-ethynylestradiol, Caffeine, Acetaminophen, Ibuprofen	Primary clarification, activated sludge biological treatment, membrane filtration, granular media filtration, granular activated carbon (GAC) adsorption, and ozonation were combined in a reclamation plant	After activated sludge treatment and membrane filtration, the concentrations of caffeine, acetaminophen, ibuprofen, tetracycline, and 17a-ethynylestradiol had decreased by more than 90%. Erythromycin and carbamazepine, being resistant to biological treatment, were eliminated by 74 and 88%, on average, by GAC. Ozonation oxidized most of the remaining compounds by >60%	[81]
Bisphenol A, Estrone, 17ß-Estradiol, 17a-Estradiol, Estriol, 17a-Ethinylestradiol, Erythromycin, Trimethoprim, Diclofenac, Ketoprofen, Metoprolol, Sulpiride, Carbamazepine, Caffeine	A full-scale anaerobic/anoxic/aerobic process combined with membrane bioreactor was used	Relatively high removal efficiency (higher than 70%) was achieved for most of the targets. The analyses of concentration distribution along the process indicate that the anaerobic tank played a key role in removing most of the targets	[82]
Carbamazepine, clofibric acid, diclofenac, iohexol	Powdered activated carbon–UF hybrid system was used	All four pollutants could be removed with an efficiency of >99%	[83]
Salicylic acid, Ibuprofen, Bisphenol A, Diclofenac, Cholesterol, Sulfamethoxazole, Sulfamethazine, Trimethoprim, Erythromycin, Clarithromycin, Roxithromycin	MBR/RO pilot plant was used. The MBR included a bioreactor that was divided into three zones (anaerobic, anoxic and aerobic) A CAS-UF/RO sequence was used	Removal efficiencies of >99% for most of the pollutants, >95% for diclofenac, and >93% for sulfonamides was achieved	[84]
Sulfonamides, sulfadiazine, sulfathiazole, sulfapyridine, sulfamethazine, sulfamethoxazole, norfloxacin, ciprofloxacin,	MBR treatment in combination with membrane filtration and ozonation was used	The removal efficiency achieved by RO technique was practically 100%. Ozonation of RO	[85]

azithromycin, erythromycin, clarithromycin, roxithromycin, trimethoprim		concentrate also resulted in a complete removal of the target pollutants	
Nalidixic acid	An integrated membrane bioreactor-ozonation process was used	The ozonation step placed in the MBR recirculation stream completely removed the nalidixic acid	[86]
Codeine, Hydrocodone, Carbamazepine, Diazepam, Lorazepam, Famotidine, Ranitidine, Azithromycin, Clarithromycin, Erythromycin, Sulfamethoxazole, Ofloxacin, Metronidazole, Atenolol, Metoprolol, Nadolol, Propranolol, Sotalol, Salbutamol, Clopidogrel	An integrated pilot scale MBR–RO system was used	The combination of MBR and RO treatment showed excellent overall removal of target contaminants with removal rates above 99% for all of them	[87]
dicloxacillin, ceftazidime	A hybrid ozonation-membrane filtration was used	Complete removal of both pollutants was achieved at a certain ozone dosing rate	[88]
Erythromycin, Sulfamethoxazole, Estriol, 17-ethynylestradiol, Estrone, 17ß-estradiol, Testosterone, Androstenedione, Iopromide, Hydrocodone, Acetaminophen, Trimethoprim, Pentoxifylline, Meprobamate, Dilantin, Naproxen, Ibuprofen, Diclofenac, Carbamazepine, Caffeine, Fluoxetine, Gemfibrozil	A membrane bioreactor followed by membrane filtration processes such as RO and NF, as well as membrane filtration processes combined with UV irradiation was used	RO and NF membrane processes showed excellent removal rates (>95%). However, the combination of membranes with UV irradiation did not increase removal. It was also found that RO did not display higher removal percentages than NF	[89]
Gemfibrozil, Ketoprofen, Carbamazepine, Diclofenac, Mefenamic acid, Acetaminophen, Sulfamethoxazole, Propyphenazone, Hydrochlorothiazide, Metoprolol, Sotalol, Glibenclamide,	Combination of UV with NF and RO was used	The highest and lowest removal efficiencies obtained by NF combination were 100 and 30%, respectively. This amount was 100 and 45% for RO combination	[90]
Diclofenac	A laboratory pilot photocatalytic membrane reactor, employing a hybrid TiO_2/UV-A catalysis ultrafiltration process was used	The system achieved more than 96% diclofenac degradation in almost all cases	[91]
Estrone, Estradiol, Estriol, Ethynylestradiol, Mestranol, Diethylstilbestrol	Combination of coagulation and nanofiltration was used	The system could remove all the six pollutants with efficiencies of more than 90%	[92]

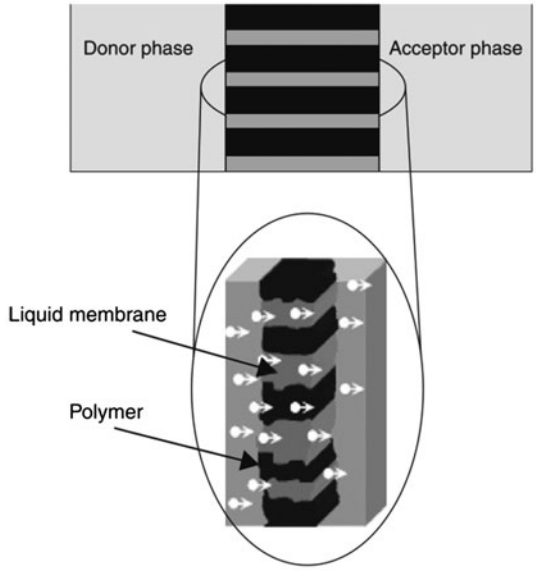

Fig. 2. A scheme of a SLM [72].

micro-pollutants from one immiscible liquid to another. The micro-pollutants of interest are transferred from the aqueous solution to the organic acceptor liquid [15,69]. Membrane-based liquid–liquid removal is a possible alternative to remove pharmaceutical compounds from water. The ability to vary flow rates independently is a significant advantage of this process. Hollow fiber membrane modules are a novel technology for the removal of trace pharmaceuticals from drinking water due to their low manufacturing cost and simple handling [70]. The performance of polypropylene hollow fiber contactors has been investigated for the removal of diclofenac sodium, ibuprofen, and its metabolite 4-isobutylacetophenone (4-IBAP) from water through liquid–liquid extraction [70,71]. Williams et al. [70] used the Liqui-Cel microporous membrane module to extract ibuprofen and 4-IBAP from water into octanol. The effects of aqueous phase pH and fluids flow rates were investigated. The removal of ibuprofen was significantly affected by pH; pH 2 was optimum for its complete removal. However, the removal of the metabolite was not influenced by this factor and nearly 96% removal was achieved for both acidic and basic solutions. Furthermore, the effects of both water and octanol flow rates on mass transfer were important [70]. In another research done by Nasirabadi et al. [71], the removal of diclofenac sodium by liquid–liquid extraction process was studied using hollow fiber contactors. 1-Octanol was used as the extractant. Fractional factorial design was applied to investigate the effects of initial concentration of the contaminant, pH of the feed, and fluids flow rates on removal efficiency of diclofenac sodium. In this study, 1-octanol could remove more than 99% of diclofenac sodium from water by polypropylene hollow fiber contactors. According to the analysis of variance, the pH and initial concentration were the most influential factors.

4.2. Supported liquid membrane

In SLM or immobilized liquid membrane (ILM), the extracting phase is supported or immobilized in the pores of the membrane while the contaminated and stripping phases flow through the shell and tube sides, respectively. The solute in water is extracted into the organic phase immobilized in the pores; subsequently, the solute in the organic phase is stripped using a suitable stripping medium. The transfer of the species by diffusion from the bulk phase occurs simply due to difference in chemical potential [15]. In fact, an SLM is a three-phase liquid membrane system in which the membrane phase (liquid) is held by capillary forces in the pores of microporous polymeric or inorganic film. The immobilized liquid is a membrane phase and the microporous film serves as a support for the membrane. Usually, SLMs are based on hydrophobic organic solvent immobilized in a polymeric membrane separating two aqueous solutions. Fig. 2 shows a scheme of a SLM [72].

The removal of 4-IBAP by ILM was studied by Williams et al. [15]. Flat and hollow fiber membranes were used in batch and continuous operations, respectively. In case of batch operation, octanol and canola oil were impregnated in a flat membrane; both solvents showed about 70% removal of the pollutant at equilibrium. Thereafter, a hollow fiber membrane module with pores impregnated with canola oil was used for the removal of 4-IBAP in both semi-batch and continuous operations using 0.1 N NaOH as the stripping solution in a recirculatory mode. About 90% of the 4-IBAP was removed in first 15 min and the percent removal steadily dropped with time, indicating that the stripping solution was getting saturated.

4.3. Forward osmosis

Forward osmosis (FO) has gained significant research interest due to the wide range of potential applications in desalination and wastewater reuse. In FO, a concentrated draw solution (DS) is used to draw water through the membrane from a feed solution (FS). The concentration or osmotic pressure difference between the two solutions acts as the driving force for water permeation through the membrane. Therefore, the FO process does not need an applied hydraulic

pressure as the traditional RO process does. The water permeating from the FS finally dilutes the concentrated DS, which exits the membrane module as a diluted DS. Depending on the final end use of the product water, the diluted DS may be required to undergo some post-treatment processes to separate draw solutes from the water, or in some cases, the diluted DS may be used directly.

During the FO process, the permeating water dilutes only to a certain extent until an osmotic equilibrium is reached between the DS and the FS. At this point, the osmotic pressure driving force disappears [73]. FO has many advantages over pressure-driven membrane processes such as lower fouling potential and simplicity [74].

Rejection of four pharmaceutical compounds, carbamazepine, diclofenac, ibuprofen, and naproxen, by FO membranes has been investigated by Jin et al. [74]. Two commercial FO membranes as well as two hand-cast ones were used. Commercial membranes were made of cellulose triacetate (CTA) supported by embedded polyester screen mesh. They were designated as CTA-HW and CTA-W. On the other hand, hand-cast membranes (TFC-1 and TFC-2) were composed of a cross-linked aromatic polyamide active layer on a polysulfone support layer.

For both TFC polyamide membranes, all compounds were efficiently removed with rejection ranging from 94 to 97%. For CTA-HW and CTA-W membranes, the rejection of pharmaceuticals followed the order of decline: carbamazepine (95–96%) ≈ diclofenac (92–95%) > ibuprofen (82–83%) > naproxen (64–73%). Moreover, the effect of pH at different levels (3, 6, and 8) was studied for TFC-1 and CTA-HW membranes. Permeate water flux of the membranes was not affected by variation of feed water pH. Using TFC-1 membrane, all four pharmaceuticals were completely or almost completely rejected over the entire pH range tested. In fact, the pH effect on the pollutants rejection was not noticeable. This indicates the stability of TFC-1 membrane performance over pH 3–8. Therefore, the size exclusion mechanism may dominate over pH-dependent mechanisms (charge repulsion and adsorption) for all selected pharmaceuticals. For CTA-HW membrane, pH influenced remarkably the rejection of naproxen and ibuprofen. As pH decreased from 6 to 3, naproxen rejection increased from 73 to 89% and ibuprofen rejection increased from 82 to 93%. As pH increased from 6 to 8, naproxen rejection increased from 73 to 93% and ibuprofen rejection increased from 82 to 93%. In contrast, the rejection of carbamazepine and diclofenac was high over pH 3–8, and the pH effect on their rejection was not noticeable [74].

In another research done by Cartinella et al. [14], the removal of two natural steroid hormones, estrone and 17ß-estradiol, was investigated using cellulose triacetate semipermeable flat sheet FO membranes (CTA, Hydration Technologies Inc., Albany, OR). Hormone rejection was greater than 99% until 20% recovery was reached. From 20 to 45% recovery, the rejection decreased steadily to 95–96%; however, from 45% recovery to the end of the experiments (70% recovery), hormone rejection increased steadily to 96–97%. Less than 1.5% difference in estrone and estradiol rejection was observed throughout the experiments.

4.4. Membrane distillation

Membrane distillation (MD) is a process in which a microporous, hydrophobic membrane separates aqueous solutions at different temperatures and compositions. Vapor pressure difference is present due to the temperature difference existing across the membrane. Thus, vapor molecules will diffuse from the high vapor pressure side to the low vapor pressure side through the pores of the membrane. MD technique has been known for over forty years since its first discovery and is currently undergoing further development and research to improve the performance for longer usage timing and better efficiency [75]. Direct contact membrane distillation (DCMD) is one of the MD configurations in which both sides of the membrane are in contact with aqueous solutions, i.e. the feed and product water streams. In DCMD, water from the heated feed stream evaporates through the membrane into the cooler permeate stream (potable water) where it condenses and becomes part of the permeate stream. DCMD is well-suited for desalination applications in which water is the desired permeating/diffusing component [14]. Hydrophobic microporous polypropylene capillary membranes were used to investigate the removal of estrone and 17ß-estradiol. Overall, the capillary membrane rejected both hormones at or above 99.5% throughout the duration of the experiments. No apparent difference between estrone and estradiol rejection was observed. Furthermore, hormone rejection was not affected by water recovery. The ability to provide greater than 99.5% hormone rejection makes DCMD an ideal wastewater treatment process [14].

5. Other processes

Yang and et al. [76] studied the removal of caffeine, acetaminophen, and sulfamethoxazole from aqueous solutions by simultaneous electrocoagulation and

electrofiltration process using composite membranes. Under the optimal operating conditions, the greatest removal efficiencies for caffeine, sulfamethoxazole, and acetaminophen were 95.8, 94.9, and 79.8%, respectively.

The removal of two antibiotics of ofloxacin and lincomycin was studied using electro-oxidation process. A membrane-divided cell was used for this purpose. Ofloxacin was oxidized efficiently on all the anodes tested. However, lincomycin was hardly oxidized [77].

6. Membrane processes in hybrid systems

MBRs and membrane filtration processes have also been used in combination with each other or other processes. Table 4 is an overview of these studies.

In most of the cases, the benefits of the integration of the applied processes have been admitted and significant results have been reported [33,78–82,87,88].

7. Overview

Application of membrane processes for the removal of pharmaceuticals from different water resources and wastewaters has been investigated in many studies. Among different membrane processes, filtrations and MBRs have been extensively studied. On the other hand, membrane contactors have attracted less attention.

In filtration processes, commercial membranes have been mostly used and NF has been the most frequent filtration type. Although RO has removed the pharmaceuticals with an efficiency of more than 80% in most of the cases, NF has also shown significant performance. For UF, the results have been so different from case to case. It is worth to mention that many of the investigated membranes have been made of polyamide. MBRs have been used for elimination of many contaminants from different pharmaceutical classes; however, it seems that more research should be done in the case of antibiotics, as the removal of a few number of pharmaceuticals of this class have been investigated using these processes. MBRs have had noticeable performance in the removal of the selected hormones and estrogens. There is a high research potential on membrane contactors, as the removal of less than 10 pharmaceutical pollutants have been studied by these processes.

Membrane processes have also been used in combination of several water treatment methods for the removal of pharmaceutical pollutants, i.e. coagulation and sedimentation, solar photo-Fenton, photo catalysis, ozonation, UV irradiation, and adsorption on granular activated carbon. The results have been significant in most of the cases.

Abbreviations

CAS	—	conventional activated sludge
CTA	—	cellulose triacetate
DCMD	—	direct contact membrane distillation
DS	—	draw solution
ELA	—	external loop air
FO	—	forward osmosis
FS	—	feed solution
GAC	—	granular activated carbon
4-IBAP	—	4-isobutylacetophenone
ILM	—	immobilized liquid membrane
MBR	—	membrane bioreactor
MD	—	membrane distillation
NF	—	nanofiltration
RO	—	reverse osmosis
SLM	—	supported liquid membrane
SRT	—	sludge retention time
STP	—	sewage treatment plant
UF	—	ultrafiltration
WWTP	—	wastewater treatment plant

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