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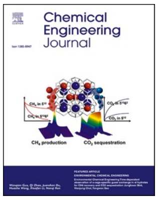

Review

A roadmap for the development and applications of silicon carbide membranes for liquid filtration: Recent advancements, challenges, and perspectives

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ABSTRACT

Water scarcity and water pollution are major issues in today’s world. Several industries including oil and gas, water treatment, wastewater treatment, and food and beverage processing have turned their attention to silicon carbide membranes to solve these issues, due to the increased water flux and enhanced mechanical, chemical, and thermal stability observed for this material. To shift the material dominance on the membrane market from polymeric and ceramic oxide to silicon carbide, a deep understanding of the fabrication of silicon carbide membranes is important. Therefore, this review focuses on the development of silicon carbide membranes from an industrial standpoint. The discussed approaches include the deposition of colloidal suspensions and polymeric precursors. In addition to describing the significant steps in the fabrication of silicon carbide membranes, the advantages, disadvantages, and remaining key challenges related to these approaches are emphasized. Furthermore, key aspects in the preparation of silicon carbide supports are presented to provide an understanding of how membrane support influences membrane performance. The wide range of silicon carbide membrane applications in water and wastewater treatment and other applications are then reviewed. Cleaning methods for silicon carbide membranes are also described to address fouling issues during filtration processes along with commercialization of these membranes. Finally, future perspectives on silicon carbide membrane material development and potential applications in other industrial sectors are discussed. Overall, this review paper aims to provide a roadmap for potential applications and further development of silicon carbide membranes in the field of liquid filtration.

1. Introduction

Based on the United Nations’ 2030 goals for sustainable development, water scarcity and a growing demand for clean water have become a major global concern [1]. Overall water consumption has increased by approximately six-fold during the last 100 years and is continuously increasing with the rapid growth of the global population, development in industrialization, and impacts of climate change [2,3]. To reduce water consumption and meet the increasing clean water demand, the protection of existing water resources and development of new water supplies are necessary—that is, by reusing, recycling, and recovering treated water. Water treatment and wastewater treatment are important processes in this regard; however, the inadequate efficiency of conventional water and wastewater technologies such as chemical coagulation [4], flocculation [5], and ion exchange [6] has led to a significant need for better treatment technologies. In this context, membrane-based technologies have been acknowledged as an effective replacement of conventional water and wastewater treatment technologies, with lower energy consumption, a smaller environmental impact, and efficient separation capability [7,8]. For these reasons, polymeric and ceramic membranes have been widely applied in many different applications over the past decades.

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Polymeric materials such as polyvinylidene difluoride (PVDF) [9], polysulfone (PSF) [10], polyamide (PA) [11], polyether sulfone (PES) [12], and cellulose acetates (CA) [13] currently dominate the membrane market because of their low synthesis and processing costs, as well as their easy preparation and scalability. However, these materials suffer from low thermal and chemical stability, which may be disadvantageous for many industrial applications, such as in the food industry, where frequent cleaning or sterilization cycles are often required. In contrast, ceramic membranes (e.g., alumina [14], silica [15], titania [16], zirconia [17], and silicon carbide [18]) posses enhanced thermal, chemical, and mechanical stability and therefore have a longer working lifespan than their polymeric counterparts. Moreover, ceramic membranes are generally highly hydrophilic, offer higher water fluxes, and have fewer fouling issues compared with polymeric membranes [19,20]. The drawbacks associated with ceramic membranes are their high processing cost and brittleness. At present, alumina is the most researched ceramic material in the field of membrane technology due to its economic competitiveness. However, silicon carbide (SiC) is rapidly emerging as a promising material in the membrane market, due to its outstanding mechanical, thermal, and chemical robustness; superior hydrothermal stability; high water permeability; and fouling resistance. Moreover, SiC membranes are suitable for application in harsh environments, such as under high temperatures and in contact with aggressive chemicals [21,22]. Thanks to these properties, SiC membranes have gained increased research interest, as shown by the exponential growth in the number of publications on SiC membranes over the last three decades (Fig. 1). Nevertheless, high fabrication temperature (up to 2100 °C) and multi-step preparation put SiC membrane at a disadvantage due to the increase in fabrication cost.

To date, several studies on the development of SiC membranes on macroporous supports have been performed using chemical vapor deposition (CVD)/chemical vapor infiltration (CVI) [23–26] or dip/spin/spray coating deposition techniques [27–32], for use in many different applications. These applications include water and wastewater treatment, gas separation, food and beverage processing, and biotechnology. The CVD/CVI method provides a denser structure compared with dip/spin/spray coating deposition techniques, resulting in lower permeability, which makes these membranes mainly suitable for gas separation applications [23,33]. By using dip/spin/spray coating deposition techniques, the structure of the separation layer can be controlled. This is necessary in order to achieve high permeability, which is a requirement for some industrial applications such as water and wastewater treatment. The two main approaches used in the dip/spin/spray coating deposition techniques are: (i) the colloidal route [27–31,34–37] and (ii) the polymeric route [23,32,38–43]. Although the polymeric route has mainly been used to fabricate gas-selective SiC, it is also applicable for water and wastewater treatment; therefore, it will be discussed in this review.

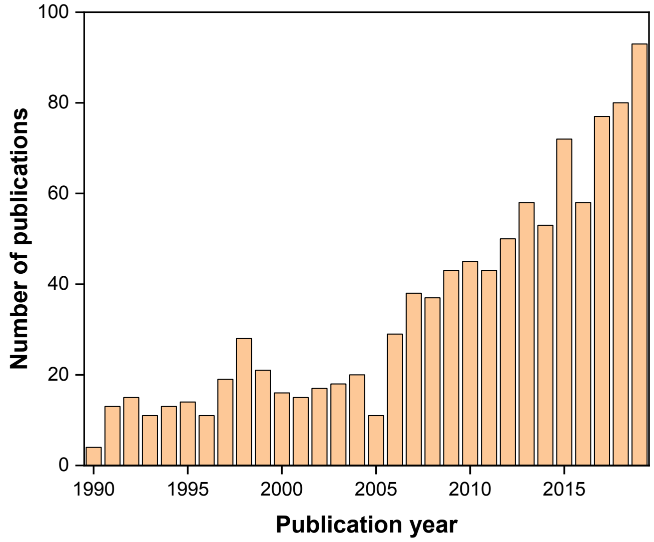

Fig. 1. Scientific publications on SiC membranes between 1990 and 2020. The initial keywords for the search were “SiC” or “silicon carbide,” which were subsequently refined for “membrane*.” (Data obtained from the Web of Science, accessed on August 17, 2020).

Microfiltration (MF) and ultrafiltration (UF) are the two main pressure-driven membrane processes, and SiC membranes developed in this way have found applications in water and wastewater treatment as well as in the food and beverage industry. Regardless of the membrane material used in these processes, membrane fouling is one of the main issues in any membrane filtration process. Therefore, efficient membrane cleaning is necessary to reduce fouling problems during filtration in order to maintain high membrane performance in terms of permeability and selectivity. The cleaning of SiC membranes, which traditionally [44,45] can be done either using chemicals (chemical cleaning) or mechanical forces (physical cleaning), is discussed herein, with a special focus on advances in the development of novel cleaning methods.

Thus far, only one review paper has been published on SiC membrane technology [46]. To the best of our knowledge, no comprehensive review of SiC membranes that focuses on water and wastewater treatment, food applications, and biotechnology applications is available at present. Considering the growing interest in SiC membranes for water treatment, wastewater treatment, and the food industry, this review presents recent advancements and challenges in SiC membrane development, along with a discussion of current and future applications. This paper is organized into two main parts. After a brief introduction, the first part of this review focuses on the fabrication methods of SiC membranes from an industrial standpoint. Key aspects of the fabrication of SiC supports are also included to provide an understanding of how membrane support affects membrane performance. The second part of this review discusses the application of SiC membranes in water and wastewater treatment and other contexts, along with cleaning methods to address membrane fouling issues. The commercialization of SiC membranes is then discussed, and future perspectives on SiC membrane material development and potential applications in other industrial sectors are addressed.

2. SiC support and membrane development

SiC membrane layers are generally fabricated on a coarse membrane support, which is also called the membrane substrate. The membrane support plays an important role in preparing defect-free and reproducible membrane layers and, by extension, in complying with industrial demand. It is desirable to obtain supports with good surface characteristics (i.e., supports that are smooth, homogeneous, and defect-free) that provide high flux, high porosity, and a high level of mechanical strength. As it meets these requirements, SiC is a promising material for the fabrication of membrane supports. Before proceeding to the preparation of SiC membranes, the key aspects of the fabrication of SiC supports are briefly presented in the following section.

2.1. Key aspects of the fabrication of SiC support

2.1.1. Manufacturing techniques

The first step toward producing a SiC support with a geometry and shape that have been optimized for a specific filtration process consists of the selection of the correct manufacturing technique. The two techniques used in the manufacturing of SiC support are: (i) dry forming and (ii) wet and plastic forming. Dry forming techniques such as uniaxial pressing and isostatic pressing limit the support to simple shapes, but do not require solvents or a pre-mixing step. Dry forming methods involve the deposition of preformed SiC particles in a mold. Next, pressure is applied to obtain the green body, which is the support before thermal annealing. The strength of this green body can be enhanced by organic binders [47–49]. Supports produced by uniaxial pressing (between 8 and 117 MPa [50–52]) are typically discs or bars with various diameters. Isostatic pressure methods are rarely considered for the fabrication of SiC supports, as they are not amenable to scale-up. Indeed, they involve a pressure between 100 and 400 MPa, which is usually applied after uniaxial pressing [53–56]. Nevertheless, such high pressures yield highly compact green bodies with enhanced sinterability, resulting in final consolidated materials with improved mechanical strength.

Wet and plastic forming techniques such as extrusion and casting allow the near-net shaping of complex geometries, which is an important requirement for the industrial fabrication of membrane supports. In these processes, SiC particles are mixed with auxiliaries in a solvent to yield a suspension or a paste. Extrusion is the most common method for producing tubular (multichannel and monotube) and flat-sheet (multichannel and disc) supports on an industrial scale due to its simplicity and ease of upscaling [31,57]. Casting a SiC support requires a lower solid content in the starting mix than that required for extrusion. In this technique, the viscosity of the resulting slurry should be adjusted so that it can run through the mold and then solidify. Manufacturing can rely on different types of casting techniques, including slip-casting [58,59], tape casting [60,61], gel casting [62], and freeze casting [63].

Fig. 2a shows the four most common geometries for commercial SiC membrane supports, all of which are fabricated by extrusion. These supports are manufactured by producing a paste with high SiC loading together with a plasticizer, a binder, and a dispersant. This paste is extruded through a specific die to produce the desired geometry. One disadvantage of these SiC supports is their relatively large pore size of up to several hundred nanometers, as shown by the micrographs in Fig. 2c. Fig. 2b also shows a hammer-shaped support, which was fabricated by combining an extruded honeycomb square part and a cup produced by slip-casting. Both parts were produced separately, and then joined with SiC paste and sintered together. This complex-shape object was originally designed as a solar receiver [64], but it can also serve as a support for dead-end filtration membranes with enhanced mechanical properties. Indeed, Fig. 2d shows that the support of a hammer-shaped geometry results in higher flexural strength than tubular and disc supports. This feature can be explained by considering that, in comparison with extrusion, casting makes it possible to produce a more compact green body, which yields a more robust support after thermal treatment.

2.1.2. *Raw materials selection*

This subsection summarizes the main characteristics of SiC supports, which can be classified as follows according to the raw materials and additives used for the fabrication: pure SiC; SiC with additives for liquid phase sintering (LPS); SiC with additives for solid state sintering (SSS); and SiC precursor materials. Raw materials should be selected to limit the production costs while simultaneously achieving the desired corrosion resistance and mechanical, structural, and filtration properties in the final membrane support. The use of pure SiC is rare, as it requires high sintering temperatures (resulting in high production costs) and makes it difficult to achieve an optimal degree of densification for producing a support with high mechanical strength [31,34]. SiC exists in

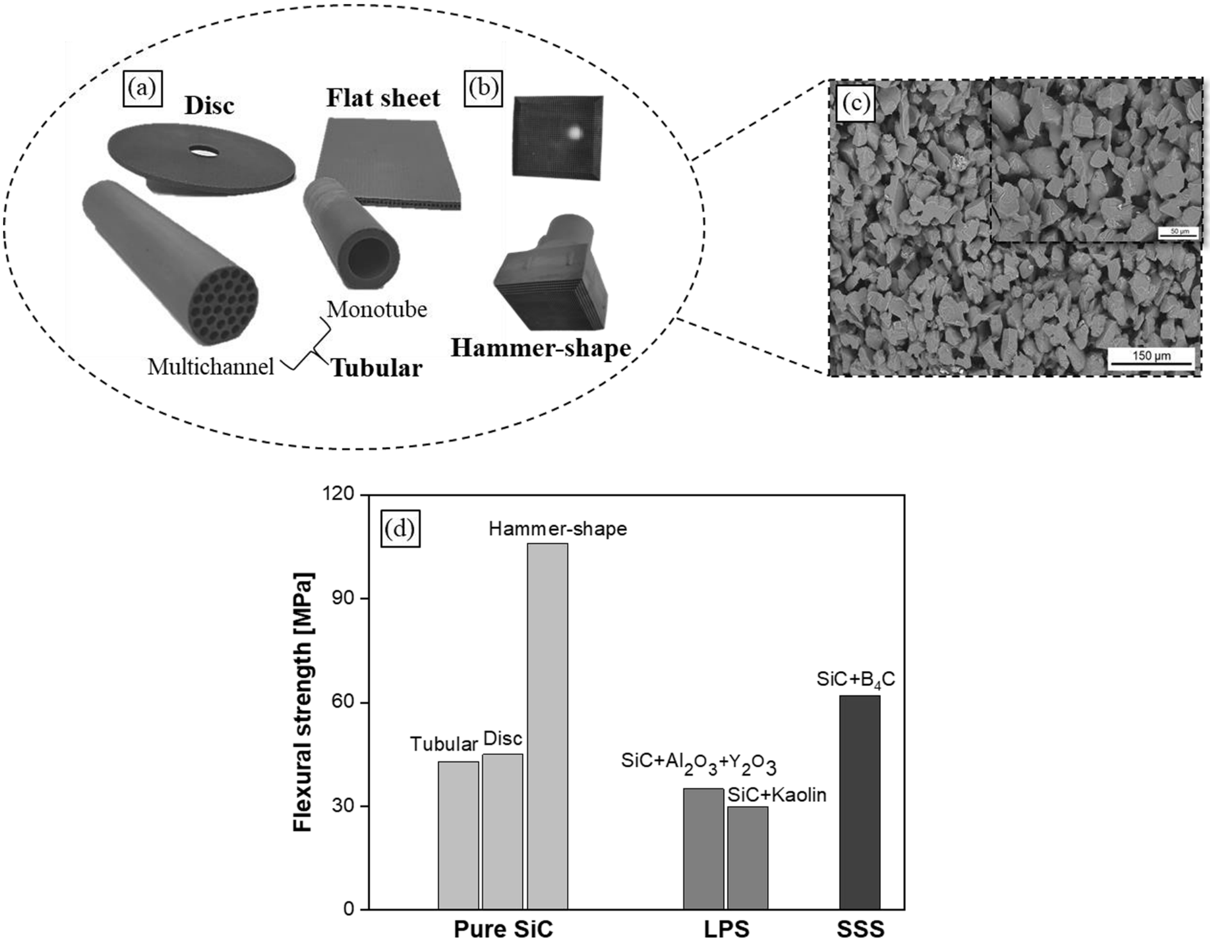

Fig. 2. SiC supports (LiqTech Ceramic A/S): (a) Commercial supports with different geometries prepared through extrusion; (b) a hammer-shape support prepared by combining extrusion and slip-casting; (c) the microstructure of a support; (d) flexural strength depending on the raw materials used and the sintering additives in the fabrication of SiC supports [57,64–66].

two main groups of polytypes, namely α and β, which have hexagonal and cubic crystal structures, respectively. α-SiC is the most commonly used SiC powder by industries, since the synthesis of α-SiC particles is less expensive and they are thermally more stable than β-SiC particles [53]. However, the sintering temperature of α-SiC (i.e., above 1700 °C) is higher than that of β-SiC (i.e., below 1700 °C). For this reason, it is possible to reduce the pore size and sintering temperature of the membrane support by combining α-SiC and β-SiC particles. The use of sintering additives is the most common approach to decrease the sintering temperature and thereby decrease production costs. In LPS, the composition and heating temperatures are chosen to develop a liquid phase during the heat treatment, which speeds up the diffusion of atoms through the liquid and increases the densification of the support material. Al_2O_3 [67,68] or a combination of Al_2O_3 and Y_2O_3 [66,69,70] are typical LPS additives for SiC. These additives can lower the sintering temperature to 1700–1950 °C and allow the fabrication of a membrane support with pore sizes within the range of 0.1–20 μm. Other oxides, such as magnesium oxide, yttria-stabilized zirconia, mullite, or zeolites, can be added to further reduce the sintering temperature. Kaolin, a type of clay, is often used to reduce the SiC sintering temperature to 1200–1500 °C [28,29,71–73]. Moreover, during sintering, kaolin is converted into the more stable mullite. In SSS, the composition and firing temperature are designed in such a way that no liquid is formed. As a result, densification is achieved by solid-state diffusion. In regard to SiC, the most commonly used additives for SSS are B_4C, graphite, carbon black, phenolic resin, or a combination of these [65,74–78]. The most common additive is a mixture of B_4C and carbonaceous materials, which retains the excellent corrosion resistance of SiC [65]. Sintering temperatures range between 1700 and 2200 °C, and a support with pore sizes between 0.4 and 10 μm can be achieved by SSS. LPS additives decrease the sintering temperature but also decrease the flexural strength (Fig. 2d). In addition, the corrosion resistance will decrease due to the residual grain boundary phases. In contrast, SSS has little effect on the sintering temperature, but the corrosion resistance is maintained and the mechanical properties are improved (Fig. 2d).

SiC support can be also fabricated by *in situ* conversion to SiC. Polycarbosilanes can be used as precursors, yielding SiC when pyrolyzed at 1100–1600 °C [79,80]. However, this method is generally more expensive than the sintering of preformed particles, due to the costs of the precursors, which are partially converted to gaseous byproducts. An alternative approach consists of the use of a natural carbon source (e.g., wood), which is melt-infiltrated with silicon and reacts to form SiC [81,82]. This method is interesting, as it relies on a renewable feedstock. Moreover, as for other wood-derived filtration materials [83–85], the selection of specific wood precursors makes it possible to tune the porosity and pore size distribution of the support. Nevertheless, purity, reproducibility, and scaling-up remain causes of concern when the final porous materials are intended for applications in membrane filtration.

2.2. Fabrication of SiC membranes

The deposition methods of SiC membrane layers are just as important as support preparation in achieving good membrane performance. The subsequent sections highlight the two main approaches—namely, the colloidal route and the polymeric route—used in the dip/spin/spray coating deposition techniques. A special emphasis is placed on how these techniques have been used for SiC tubular and flat-sheet membrane development, along with their pros and cons. The preparation technique of SiC hollow-fiber membranes is also discussed. Table 1 presents a summary of the studies performed on the development of SiC, in respect to support materials, raw materials, deposition techniques, membrane thickness, thermal treatment, and other remarks.

2.2.1. Deposition of colloidal suspensions

The traditional and simple way to prepare SiC membranes is coating with colloidal suspensions. This approach is also known as ceramic processing. A general schematic illustration of the fabrication steps for the specific case of tubular SiC membranes is shown in Fig. 3a. In this method, the SiC membrane formation consists of six steps: (i) selection of the raw material; (ii) mixing of the raw materials; (iii) homogenization of the suspension; (iv) addition of binder to the suspension; (v) coating; and (vi) sintering of the green body. This technique has been broadly applied by the scientific community and industries, since it is simple, easy to control, and easy to scale up to an industrial level [27–31,34–37].

In this multi-step process, each step has its specific role for obtaining high-quality membranes. Many researchers have reported the preparation of SiC membranes through the ceramic processing approach (Table 1). After the selection of raw materials, preparing a homogenous suspension of SiC powder is the one of the most crucial steps. This is because the formation of the desired SiC membrane relies on the complete dispersion of SiC particles in the solvent. Therefore, dispersants (e.g., methyl cellulose (MC) [27,36], ammonium polymethacrylate (Darvan-CN) [28,29], tetramethylammonium hydroxide (TMAH) [30], polyacrylic acid (PAA) [31,34], and synthetic polyelectrolyte (Produkt-KV5088) [37]) are usually added in this step with the aim of enhancing the homogeneity of the dispersion. Once the suspension is homogenized, a binder (e.g., polyvinyl alcohol (PVA) [28–30,35], polyethylene glycol (PEG) [28,29], sodium carboxymethyl cellulose (CMC) [31,34], or polysaccharide dicarbonic acid polymer (Optapix CS-76) [37]) is added to the suspension to improve the mechanical strength of the green body. The suspension is further stirred, and defoaming agents (e.g., TL-56NQ [27,36]) can also be added to prevent foam formation. The addition of the right amount of binder, dispersant, defoaming agent, and SiC powder to the suspension plays a vital role, since different amounts change the rheological properties of the colloidal suspension. For example, Bukhari et al. [28] investigated the effect of the amount of dispersant on the viscosity of SiC suspension for different solid loadings. It was found that the change in the suspension viscosity affects the thickness and uniformity of the membrane layer. A suspension with high viscosity may cause thicker coatings and, consequently, increase the chance of defect formation at the membrane surface. On the other hand, a suspension with low viscosity may cause infiltration of SiC particles in the macropores of the support. Therefore, the right formulation of SiC suspension with the raw materials is crucial to form the desired morphology of the membrane layer. In the next step of processing, the prepared suspension is used to coat the macroporous membrane support by means of various coating techniques such as dip-coating [28–31,37] or spray coating [27,34,36]. Dip-coating is one of the most widely used methods because of its relative simplicity [86]. During the fabrication procedure, the coating method plays an important role in controlling the film thickness of the selective layer. From Table 1, it can be seen that the thicknesses of the membrane layers formed by the dip-coating technique are in the range of 0.16–100 μm, while the thicknesses of membranes formed by spray coating vary in the range of 60–200 μm. After coating, the membrane layer is sintered at temperatures up to 2100 °C. In this approach, high sintering temperatures are required to obtain SiC membranes with the desired physical and chemical properties. Several studies have reported the use of low melting point sintering additives (e.g., CaO, ZrO_2, B_4C, and MgO) to reduce the high sintering temperature. Recently, alumina, alumina and yttria, boron and graphite, and iron have been employed as sintering additives in the formulation of SiC suspensions by LiqTech Ceramics. These membranes were fabricated on a commercial SiC support with sintering temperatures in the range of 1600–1900 °C. When Al_2O_3, Al_2O_3-Y_2O_3, and Fe were used as respective sintering additives, the sintering temperature was 150 °C lower than when boron and graphite were used. The lower sintering temperatures in the cases of Al_2O_3, Al_2O_3-Y_2O_3, and Fe could be ascribed to the formation of a low-viscosity liquid phase, which promotes the mass transfer of the atoms at lower temperatures [87]. The structural morphology of the membranes in the presence of different sintering additives is shown in Fig. 3b to e. As can be observed, the junction between the grains is clearly visible in all

Table 1

Summary of studies performed on the development of SiC membranes via deposition of colloidal solution, deposition of pre-ceramic polymeric precursors, and dry-wet spinning methods.

	Support material/ membrane layer material	Raw materials (starting powder, precursor, solvent, additives)	Membrane deposition technique	Membrane thickness [μm]	Thermal treatment	Remarks	Ref.
DEPOSITION OF COLLOIDAL SOLUTION	SiC (discs)/SiC	α-SiC powder (10 μm)SiC whisker, mullite[5], CaO[5], ZrO$_2$[5], methyl cellulose (MC)[2], TL-56NQ[4], water[1]	Spray coating	~125–200	1150–1250 °C/2h in air;1350–1500 °C/4h in argon (Ar)	• Defect-free SiC membranes • Average pore size of 2.31 μm • Excellent corrosion resistance in both H_2SO_4 and NaOH solutions • Excellent thermal shock resistance	[27]
	SiC (flat sheet)/ SiC	α-SiC powder (0.55 μm), deionized water[1], *iso*-propyl alcohol (IPA)[1], polyvinyl alcohol (PVA)[3], polyethylene glycol (PEG)[3], Darvan-CN[2]	Dip-coating	~12–30	900–1300 °C/1h	• Crack-free oxidation bonded SiC membranes • Average pore size of 93 nm • Optimization of the slurry and controlling the oxidation behavior of SiC examined	[28]
	SiC (flat sheet)/ SiC	α-SiC powder (0.55 μm), deionized water[1], *iso*-propyl alcohol (IPA)[1], polyvinyl alcohol (PVA)[3], polyethylene glycol (PEG)[3], Darvan-CN[2]	Dip-coating	~20	1000 °C	• Stable oxidation bonded SiC membranes • Controlled oxidation parameters • Average pore size of 78 nm • Good corrosion resistance under low and high pH conditions	[29]
	SiC (flat sheet)/ SiC	SiC powder (22 μm), B_4C[5], polyvinyl alcohol[3], tetramethylammonium hydroxide (TMAH)[2], water[1]	Dip-coating	~100	2200–2250 °C	• SiC membranes prepared by co-sintering process • Good mechanical properties • Average pore size of 9.93 μm	[30]
	SiC (flat sheet)/ SiC	SiC powders (0.5 μm and 3 μm), polyacrylic acid (PAA)[2], sodium carboxymethyl cellulose (CMC)[3], water[1]	Dip-coating	~60	1900–2000 °C in vacuum	• SiC membrane layer with homogeneous structure • The effect of particle size on pore size, mechanical strength examined • Average pore size of 0.5 μm and 1.4 μm for membranes prepared from 0.5 μm powder and 1.5–2.1 μm for membranes prepared from 3 μm SiC powder	[31]
	SiC (flat sheet)/ SiC	SiC powders (1 μm), polyacrylic acid (PAA)[2], sodium carboxymethyl cellulose (CMC)[3], water[1]	Spray coating	~60	1850–1900 °C/1h in vacuum	• Smooth and defect-free SiC membrane layers • Average pore size of 0.5–0.65 μm • Larger pores obtained with the increase in sintering temperature	[34]
	SiC /SiC	α-SiC powder (5 μm), NaA zeolite residues[5], activated carbon (AC)[7], polyvinyl alcohol[3], water[1]			850–1050 °C in air	• Reduced sintering temperature • Good mechanical stability • Increased porosity • Pore size adjusted by doping different amount of NaA (r) and AC • Strong long-term acidity and caustic corrosion	[35]
	SiC (disc)/SiC	SiC powders (5 μm, 10 μm, 15 μm, 300 μm), MgO[5], ZrO$_2$[5], Al-DTPA microfibers, methyl cellulose[2], water[1], TL-56NQ[4],	Spray coating	~100	1200 °C/2h in air; 1300 °C/2h in Ar	• Defect-free, transition layer-free separation layer • Particle penetration is avoided by using Al-DTPA microfibers as the transition layer • Average pore size of 2–5 μm	[36]
	SiC (tubular) /SiC	α-SiC powders (0.2 μm, 0.4 μm, 0.6 μm, 0.8 μm), Produckt-KV5088 (PKV)[2], Optapix CS-76[3], water[1]	Dip-coating	~11–46	1500–1900 °C/4h in Ar	• Defect-free membranes obtained with 16–22 wt % solid loading for the blend of 0.2 and 0.6 μm SiC powders • Reduced sintering temperature without using sintering additives	[37]
DEPOSITION OF PRE-CERAMIC POLYMERIC PRECURSORS	SiC (flat discs)/SiC	Allylhydridopolycarbosilane (AHPCS)[6], hexane[1]	Dip-coating		400 °C/1h600–1600 °C/2h in Ar	• Nanoporous membranes	[23]
	SiC (tubular)/SiC	SiC powder (0.6 μm), acetone[1], AHPCS[6], hexane[1]	Slip-casting + dip-coating	~2	200 °C/1h400 °C/ 1h750 °C/2h in Ar;450 °C/ 2h in air	• Combining slip-casting and dip-coating significantly improved the reproducibility in preparing high-quality membranes • Microporous membranes • Good hydrothermal stability	[32]

(*continued on next page*)

Table 1 (*continued*)

	Support material/ membrane layer material	Raw materials (starting powder, precursor, solvent, additives)	Membrane deposition technique	Membrane thickness [µm]	Thermal treatment	Remarks	Ref.
	α-Al2O3 (tube)/ SiC	Polycarbosilane (PCS)[6], toluene[1], polystyrene (PS)	Dip-coating		200 °C /1–10 h700 °C/2h in Ar	• Thin and defect-free membrane • Improved membrane performance thanks to the addition of PS, appropriate oxidation of the membrane, and low temperature thermal crosslinking • Pore diameter of 0.5–0.7 nm	[38]
	SiC (tubular)/SiC	SiC powder (0.6 µm), acetone[1], polystyrene (PS)[7], toluene[1], AHPCS[6], hexane[1]	Slip-casting + dip-coating	~7	200 °C/1h400 °C/ 1h750 °C/2h in Ar;450 °C/ 2h in air	• The periodic coating of sacrificial PS interlayers in between AHPCS layers • Nanoporous SiC membranes • Improved membrane characteristics due to the sacrificial interlayers • Thicker membranes	[39]
	SiC (tubular) /SiC	SiC nanofibers, β-SiC powder (0.1 µm – 0.2 µm), AHPCS[6], toluene[1], hexane[1], polystyrene (PS)[7]	Slip-casting + dip-coating	~10	200 °C/1h400 °C/ 1h750 °C/2h in Ar;450 °C/ 2h in air	• Increased success rate in preparing high-quality membranes • Microporous SiC membranes prepared with the aid of nanofiber-based mid-layers • Spherical nonporous nano-powders resulted in better membrane characteristics	[40]
	SiC (flat discs)/SiC	α-SiC powder (0.4 µm), AHPCS[6], hexane[1], hexane-tetradecane[1]	Dip-coating	~8–22	200 °C/1h400 °C/ 1h750 °C/2h in Ar	• The effect of particle size, type of solvent, and precursor/SiC powder mass ratio on the optimization of the suspension were examined • Defect-free SiC membrane for UF applications • Membranes consist of two size orders of pores: pores smaller than 5 nm and large mesopores	[41]
	α-Al_2O_3 (tube)/SiC	α-alumina particles (0.2 µm, 2 µm); SiO_2-ZrO_2 sols[3], polycarbosilane (PCS)[6], p-xylene[1]	Dip-coating		150–300 °C/2h in air; 750 °C/0.5 h in N_2	• Tailored membrane microstructure via controlling the thermal oxidative curing process • Stable and uniform microporous membrane structure • High thermal stability and oxidation resistance at 500 °C	[42]
	α-Al_2O_3 (tube)/SiC	α-alumina particles (0.2 µm, 2 µm); SiO_2-ZrO_2 sols[3], AHPCS[6], toluene[1]	Dip-coating	~0.16	300–800 °C/0.5 h in N_2	• Thin, crack-free, and continuous separation layer • The coating solution of pre-crosslinked AHPCS reduced penetration into support	[43]
DRY-WET SPINNING	SiC hollow fiber	α-SiC powders (0.4 µm, 0.6 µm), polyethersulfone (PES)[3], n-methyl-2- pyrrolidone (NMP)[1], water	Dry-wet spinning		300–1500 °C in N_2; 300–2075 °C in Ar	• Hollow-fiber membranes with outer diameters of 1.8 mm • The pore size and mechanical strength of hollow fibers optimized by changing sintering temperature	[88]
	SiC hollow fiber	α-SiC powders (3.54 µm, 3.09 µm), polyethersulfone (PES)[3], n-methyl-2- pyrrolidone (NMP)[1], polyvinylpyrrolidone (PVP), water	Dry-wet spinning	0.3 mm wall thickness	2050 °C/2h in Ar	• Hollow-fiber membranes with outer diameters of 2 mm • Uniform and narrow pore size distribution • Average pore size of 0.71 µm	[89]

Blank spaces correspond to unavailable data.

[1] solvent; [2] dispersant; [3] binder; [4] defoaming agent; [5] sintering additive; [6] polymeric precursor; [7]pore former.

of these cases. Defect-free and homogeneous layers with small pore sizes were obtained in the cases of Al_2O_3 (Fig. 3b), Al_2O_3-Y_2O_3 (Fig. 3c), and Fe (Fig. 3d). However, the higher sintering temperature in the case of boron and graphite generated some defects in the membrane layer (Fig. 3e) and caused larger pore sizes. Even though these additives lower the sintering temperature, they introduce a glassy phase between SiC grains, since they are generally metals and/or metal oxides. This results in a decrease in the corrosion resistance and thermal shock resistance of the membrane [31]. Upon sintering, membranes are heat treated under air to remove the free carbon that is eventually formed in the pores.

However, there are still drawbacks to this fabrication method that need to be investigated in detail in order to advance the fabrication of SiC membranes on an industrial scale. Firstly, a large amount of alcohol is usually used as a solvent to prepare well-dispersed coating suspensions. This can cause environmental issues due to toxicity as well as health and safety problems due to handling large volumes of solvent in a production setting. Therefore, environment-friendly solvents should be used to avoid the issues derived from the use of organic solvents. For example, the preparation of a water-based coating suspension would be an effective approach. Secondly, the typical structure of a SiC membrane consists of multiple layers on a macroporous support. Depending on the application, the number of layers can be as many as four or more in order to generate upper layers with smaller pores. This means that, after the coating of each layer, the green body must undergo high-temperature sintering before the coating of the next membrane layer. The consecutive coating of the layers and sintering steps make the production of SiC membranes costly. The industrial-scale production of SiC membranes could be more economically viable if additional research efforts were made on minimizing the number of the layers and thereby minimizing the number of sintering steps.

2.2.2. *Deposition of pre-ceramic polymeric precursors*

Another well-known approach in the fabrication of SiC membranes is the deposition of pre-ceramic polymers as a precursor. A general schematic illustration of the pre-ceramic polymeric precursor route, for the specific case of flat-sheet SiC membranes, is shown in Fig. 4. SiC membrane formation involves three main steps: (i) shaping/coating in order to give the polymer a particular form; (ii) curing for the crosslinking of the polymer; and (iii) pyrolysis to transform the cured polymer into a ceramic [90]. The pre-ceramic polymeric route has gained attention over other methods not only because of its simplicity, but also because of its rather low pyrolysis temperatures (750–1000 °C) in comparison with the partial sintering of SiC. In addition, the pre-ceramic polymeric precursor method has advantages in terms of fabricating membrane materials with a controlled structure (e.g., composition, shape, porosity, and pore size), which eventually affects membrane performance.

In the past decades, there have been various studies on fabricating SiC membranes using different polymeric precursors such as polycarbosilane (PCS) [21,22] and polydimethylsilane (PMS) [91,92]. These polymeric precursors are generally curable in the presence of oxygen. However, the curing process introduces a significant amount of oxygen into the final SiC membrane structure, which reduces the thermal and hydrothermal stability of these membranes. To overcome this drawback, different curing methods (e.g., UV radiation [93], electro-beam irradiation [94], or heat treatment under an inert atmosphere [95]) and a new type of polymeric precursor—namely, allylhydridopolycarbosilane (AHPCS), which is a partially allyl-substituted hydridopolycarbosilane (HPCS)—have been widely researched. The reasons for choosing AHPCS as a new type of polymeric precursor include its liquid form, easy processing compared with PCS, and curing efficiency under an inert atmosphere, which results in an enhanced ceramic yield in the resulting SiC membrane [96]. Selected studies performed on the development of SiC membranes by the pyrolysis of pre-ceramic polymers are also summarized in Table 1. For example, Ciora et al. [23] prepared SiC nanoporous membranes on SiC flat discs using AHPCS as a polymeric precursor by means of the dip-coating technique, followed by pyrolysis under an argon (Ar) environment. Similarly, Elyassi et al. [32,39,40] reported several membrane-preparation procedures for SiC membranes on SiC tubular supports with improved membrane characteristics and performance using AHPCS as a polymeric precursor. In these studies, the membranes were prepared using a combination of slip-casting and dip-coating techniques. Coating the SiC macroporous support by slip-casting prior to dip-coating significantly improved the reproducibility of preparing high-quality membranes [32].

Although the pre-ceramic polymer method provides various possibilities to control the properties of SiC membranes, challenges still remain. The penetration of polymeric precursors into the pores of the support must be avoided to prevent subsequent crack formation due to uneven shrinkage of the structure during the polymer-to-ceramic transformation. Moreover, multiple layer coatings and pyrolysis steps are needed to minimize defect formation, which eventually makes the processing of SiC membranes economically unfeasible. Konig et al. [41] tried to solve these issues by fabricating AHPCS-derived mesoporous SiC membranes on a SiC support in the presence of sub-micrometer SiC filler. In this way, crack formation can be avoided and nearly defect-free and uniform mesoporous SiC membrane layers can be obtained, with a one-step layer coating and pyrolysis of the AHPCS precursor at 750 °C in Ar. The effects of the coating suspension parameters (e.g., type of solvent, loading of SiC fillers, and AHPCS/SiC ratio) on the preparation of defect-free SiC membrane layers were investigated in the same study. Other studies have suggested different membrane-preparation procedures to prevent the penetration of polymeric precursors into the substrate and to avoid crack formation during the fabrication of SiC membrane layers. For example, Elyassi et al. [39] and Dabir et al. [97] suggested the dip-coating of sacrificial polystyrene interlayers along with SiC pre-ceramic layers on top of a slip-casted tubular SiC support for preparation of SiC nanoporous membrane. Recently, Wang et al. [43] attempted to fabricate a SiC membrane on an α-Al_2O_3 support layer by pre-crosslinking an AHPCS solution at 150 °C for 2 h under a nitrogen (N_2) atmosphere prior to coating the AHPCS-derived SiC top layer onto an intermediate layer. The pre-crosslinking of the AHPCS resulted in the formation of larger colloidal sol sizes, and therefore minimized the penetration of the coated precursor into the support, thereby avoiding crack formation.

Despite the fascinating advantages of the pyrolysis of pre-ceramic polymer precursors method, it is still challenging to fabricate SiC membranes with a high porosity and narrow pore size distribution, especially for nanofiltration (NF) and UF applications. Recently, there has been growing interest in adopting new synthesis strategies to tailor the structure of SiC membranes [42,98]. However, more research effort is still needed in controlling the pore size, porosity, and thickness of the selective layer, as well as upscaling a chosen approach in order to achieve good membrane performance for potential applications.

The advantages and disadvantages of both of the two main approaches discussed thus far for the preparation of SiC membranes are summarized in Table 2.

2.2.3. *Dry-wet spinning*

In addition to SiC membranes with tubular and flat-sheet configurations, SiC membranes with hollow-fiber geometry (Fig. 5a and b) have been fabricated by means of the dry-wet spinning technique [88,89]. This technique consists of phase inversion and sintering steps. To prepare hollow fibers, a polymeric binder dissolved in an organic solvent in the presence of SiC particles is used as a suspension. The suspension extrudes through a spinneret and coagulates in a non-solvent (e.g., water) bath. Due to the solvent and non-solvent exchange, phase separation into a polymer-lean and a polymer-rich phase occurs. This phase separation results in a sponge-like structure containing finger-like voids in the morphology of the hollow fibers (Fig. 5c) [99]. SiC hollow-fiber membranes have the advantages of larger effective filtration area per unit volume of the membrane, controllable microstructure, and high membrane permeability compared with other geometries. However,

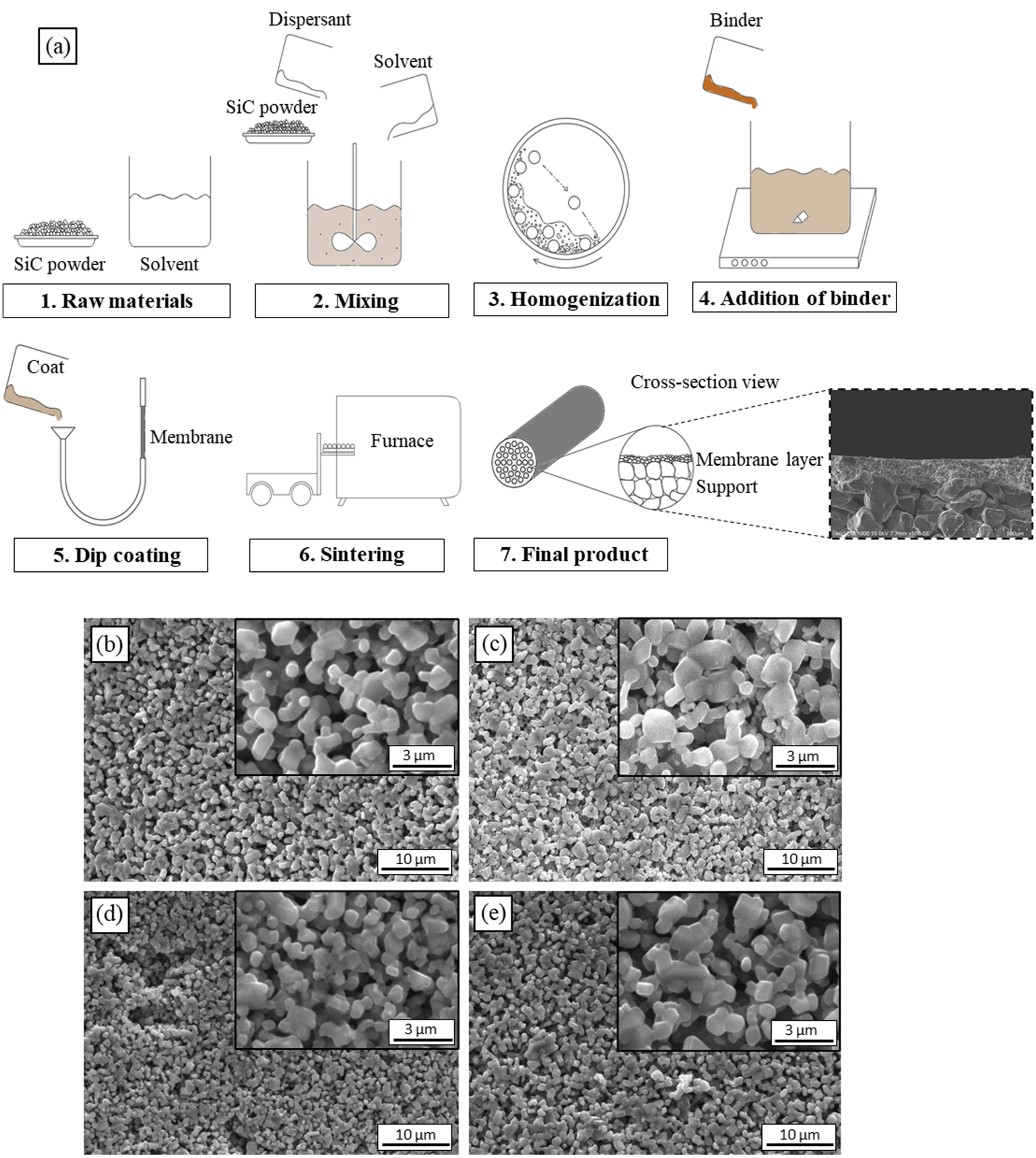

Fig. 3. (a) Schematic illustration of the fabrication steps of a tubular SiC membrane through ceramic processing and SEM images of the surface microstructure of SiC membranes fabricated with different sintering additives: (b) alumina; (c) alumina and yttria; (d) boron and graphite; (e) iron.

their poor mechanical stability and brittleness limit their usage by industries. Therefore, the development of SiC hollow-fiber membranes is still only at an academic level.

3. Applications of SiC membranes

The above section presented and discussed the preparation of SiC supports and membranes. The key properties of developed SiC membranes give these membranes great potential for use in many different applications. In this section, therefore, the modes for filtration are reviewed along with the various applications of SiC membranes in water treatment, wastewater treatment, and other contexts. The results from different applications of SiC membranes are summarized in Table 3.

3.1. SiC membrane filtration modes

SiC membrane filtrations are pressure driven, and applications can be defined in three main categories: crossflow, dead-end, and semi-dead-end filtration. During crossflow filtration, a flow tangential to the membrane surface provides shear forces that wash away fouling, such as filter cakes of small particles or biofouling. The induced crossflow is significantly larger than the permeate flow through the membrane in order to reduce deposition of material onto the membrane. Crossflow filtration offers advantages when a large fraction of the total suspended solids (TSS) consists of smaller particles, as continuous operation can be carried out [100,101]. In the dead-end configuration, the feed flow is perpendicular to the membrane, and all of it passes through [102]. This is the simplest configuration and must be operated in batch mode, as

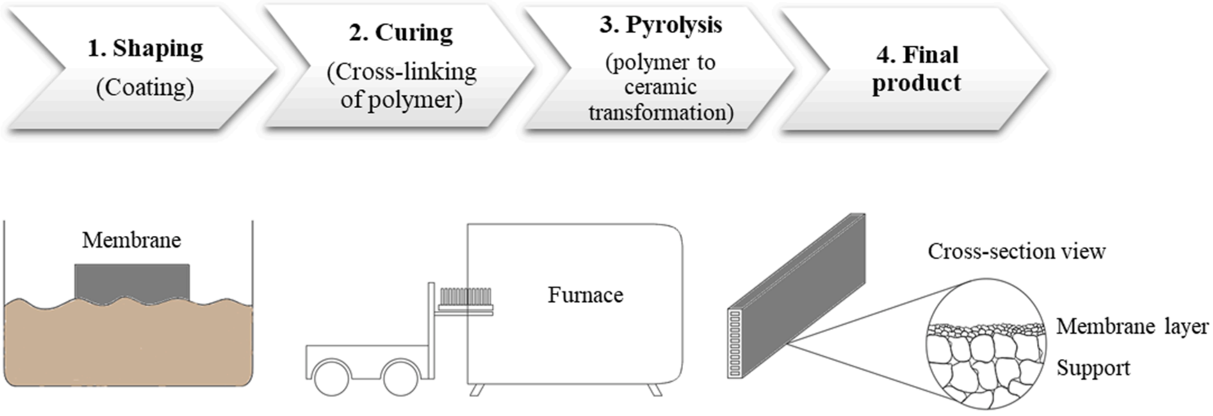

Fig. 4. Schematic representation of the synthesis procedure of a flat sheet SiC membrane via the pre-ceramic precursors route.

Table 2
Summary of the advantages and disadvantages of the colloidal and pre-ceramic polymer approaches used to fabricate SiC membranes.

	Deposition of colloidal solutions	Deposition of pre-ceramic polymeric precursor
Advantages	• Simple route • Easy to control • Easy to scale-up	• Simple route • Membranes with controlled structure • Low pyrolysis temperature
Disadvantages	• High sintering temperature • Multiple layer coatings • High cost • Limitation on membrane pore size	• Potential blocking of pores due to penetration of the polymeric precursor • Shrinkage of structure • Multiple layer coatings

there is no built-in discharge of the retentate. Dead-end filtration is beneficial when dealing with relatively clean feedwater or, on the other end of the spectra, when feed waters with high TSS levels make a crossflow difficult or impossible to perform. The submerged membranes in membrane bioreactors are an example of the latter situation [103,104]. Semi-dead-end filtration is similar to dead-end filtration in that all of the feed flow passes through the membrane. However, semi-dead-end filtration can be operated continuously, as the membrane vessels allow periodical flushes to empty the high-pressure side of the membrane for concentrated retentate with a backwash. This configuration is typically chosen for medium TSS levels—that is, when there are too many suspended solids for an efficient true dead-end filtration but not enough for an efficient crossflow filtration [105]. Submerged membranes, such as the flat-sheet membranes in membrane bioreactors, may be categorized as being in a semi-dead-end filtration mode.

3.2. *Wastewater treatment*

3.2.1. *Oily wastewater*

Due to their high chemical resistance, SiC membranes are robust and can withstand periodical chemical cleaning, which is applied in wastewater treatment. As an example, olive oil production results in the production of large amounts of wastewater with high levels of oils and other organic compounds such as polysaccharides, phenols, and proteins. MF membranes from LiqTech have been studied for the treatment of olive mill wastewaters, and showed high removal efficiency of suspended solids (>99%) oil and grease (75%–84%), and chemical oxygen demand (COD) (38%–53%) as shown in Fig. 6a [117]. The membrane was operated in crossflow mode (2 m/s) at a flux of 100 LMH, with the TMP increasing from 0.02 to 0.50 bar over the 7 h of filtration due to membrane fouling. However, back-pulses every 10 min and hourly backwashes proved to efficiently mitigate and remove fouling, while chemical cleaning at 60 °C with 4% (w/w) NaOH efficiently removed oil and grease as well as other organic compounds from the membrane surface.

The performance of membranes for treatment of produced water has been studied by comparing different membranes made of polytetrafluoroethylene (PTFE), polyvinylidene fluoride (PVDF), polyacrylonitrile (PAN), ZrO_2 and SiC [121]. The study showed that PTFE and SiC membranes outperformed the other membranes in terms of low development of irreversible fouling, as both membrane materials have high chemical stability and heat resistance, thus they can efficiently be cleaned at high temperatures and in a wide range of pH [46,122]. However, due to their hydrophilic surface and high chemical resistance, SiC membranes show superior water permeability and oil retention, hence good potential for separations in the oil and gas industry [106–109,121]. Zsirai et al. [106] compared the water permeability and retention of oil and grease (O&G) during the MF and UF filtration of produced water with SiC and TiO_2 membranes. Comparable removal

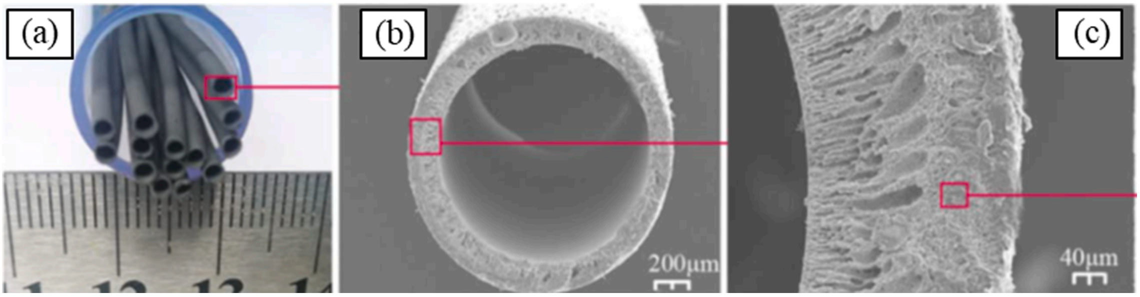

Fig. 5. (a) Macroscopic view; (b) SEM image of the overall cross-section; (c) SEM image of a local enlarged cross-section of the SiC hollow-fiber membranes reported in Ref. [89]. (Published by the Royal Society of Chemistry).

Table 3
Summary of results from the literature on the application of SiC membranes.

Application	Membrane	Filtration mode	Flux	Remarks	Ref.
Produced water	SiC MF[1] and UF[2]	Crossflow (pilot)	1300–1800 LMH[3]	• SiC membranes have higher permeabilities than TiO_2 but also higher fouling propensities • 70%–80% oil removal for MF, 80%–90% for UF	[106]
Produced water	SiC MF and UF	Crossflow (pilot)	700 LMH long-term flux, i.e., 1300 LMH/bar permeability	• Citric acid, NaOH, and backwash are efficient for membrane cleaning • Membranes become more hydrophobic over time	[107]
Shale flowback water	SiC MF	Dead-end	20%–90% flux decline depending on flowback water composition	• Floc breakage affects membrane fouling	[108]
Oily wastewater	UF	Crossflow		• 96% oil rejection • Optimal crossflow velocity 0.5 m/s	[109]
Oily wastewater	>MF (pore size 3.7–6.5 µm)	Dead-end		• 89%–93% oil retention (oil concentration of 1557 mg/L) • >13000 LMH/bar pure water pure water permeability	[110]
Oily wastewater	MF flat sheet	Submerged membrane (membrane bioreactor)	10–15 LMH	• SiC employed as a submerged flat sheet in membrane bioreactor (MBR) • Efficient removal of pollutants: heavy metals (29%–97%), phenols (up to 100%), BTEX (up to 100%), PAHs (up to 100%), and total organic carbon (TOC) (96%–98%)	[111]
Synthetic oily wastewater	MF	Dead-end	64 LMH steady-state flux trans membrane pressure (TMP) = 1 bar		[112]
Backwash water and dam water	SiC MF	Dead-end (pilot)	102–280 LMH	• Efficient removal of particles by SiC membranes • Higher backwash cleaning efficiency and less fouling than polymeric membranes	[113]
Surface water	SiC UF	Semi-dead-end	150 LMH	• SiC and TiO_2 membranes less prone to fouling than Al_2O_3, ZrO_2, and polymeric membranes	[114]
Drinking water Arsenic removal	SiC MF	Dead-end (pilot)	400–600 LMH, 0.25 bar	• 95% arsenic reduction • Efficient backwash in semi-dead-end mode	[115]
Swimming pool water treatment	SiC MF	Dead-end	45.7 LMH	• Removal of submicron-sized particles is higher for SiC MF membranes than for conventional sand filters	[116]
Olive mill wastewaters	SiC MF	Crossflow	100 LMH, 0.02–0.50 bar TMP	• 75%–84% removal of oil and grease, removal of suspended solids	[117]
Membrane bioreactor	SiC MF	Submerged membranes	20 LMH	• High chemical oxygen demand (COD) removal (94%) with SiC-coated inorganic membrane	[118]
Anaerobic membrane bioreactor for domestic and food wastewater	SiC MF	Submerged membranes	10 LMH	• 93.5% organic removal efficiency • Methane productivity 0.094 ± 0.069 L CH_4 g^{-1} COD removed • Operation at high total and volatile solids concentrations	[119]
Microalgae harvesting	SiC MF	Immersed	60 LMH	• Dosing PaCl reduces fouling layer resistance and irreversibility and polysaccharide concentration in permeate	[120]

Blank spaces correspond to unavailable data.

[1] MF: microfiltration; [2] UF: ultrafiltration; [3] LMH: flux unit (l/h/m^2)

rates of O&G were found with the MF and UF SiC and TiO_2 membranes (70%–80%), but the permeability of the SiC membranes was significantly higher than that of the TiO_2 membranes. Higher permeability is beneficial for low-footprint installations, which are crucial in oil and gas industry applications. However, the membranes were found to be prone to membrane fouling, calling for efficient cleaning strategies to sustain permeability. This study was followed by an analysis of backwash and cleaning in place (CIP; using 6% (w/w) NaOH and citric acid) for periodical membrane cleaning [107]. The analysis showed that a flux of 700 LMH (transmembrane pressure (TMP) = 0.55–0.60 bar) could be sustained. However, it was found that the membrane surface became more hydrophilic during filtration. It was estimated that the high permeability enables a flow per footprint area of 7.2 m/h (m^3/m^2/h) for a Veolia system and 7.8 m/h for a LiqTech system. These footprints are slightly lower than the footprint of induced gas flotation upstream to the filtration system. He and Vidic [108] compared the performance of SiC and Al_2O_3 MF membranes in terms of fouling propensity during the filtration of flowback water. However, no effect of electrostatic interactions on the fouling of the two membranes was found, due to the high salinity of the flowback water. The main fouling mechanism was intermediate pore blocking and was severely elevated by oil floc breakage at high shear levels. On the other hand, Zoubeik and Henni [109] found that the main fouling mechanism during UF with a SiC UF membrane (0.04 µm pore diameter) was cake formation. To reduce cake formation, an optimal crossflow velocity of 0.5 m/s was applied, along with a TMP of 0.9 bar. These contradictory results regarding fouling mechanism may be a result of different pore sizes, as MF membranes with larger pore sizes are more prone to pore blockage than UF membranes. A strategy to reduce membrane fouling involves the surface modification of membranes. In this regard, it has been shown that SiC membranes (10 µm particles for support and 2 µm SiC particles for intermediate support layer) can be coated with γ-Al_2O_3 to reduce fouling while elevating oil rejection to 99.9%. A steady-state flux of 64 LMH was reached at 1 bar TMP. Although most studies have shown the ranges of oil retention in MF and UF ranges, Das et al. [110] showed high oil retention (89%–93%) even with pore sizes as large as 3.7–6.5 µm. This finding can be explained by the hydrophilicity of the SiC material, but also depends on the stability of the oil-in-water suspension.

An alternative to the direct filtration of oil and gas wastewater treatment is to apply membranes in a membrane bioreactor (MBR) that employs simultaneous biological degradation and filtration. This has been demonstrated at the pilot scale using submerged flat-sheet SiC membranes. The results show efficient removal of heavy metals (retained in sludge, 29%–97%), phenols (up to 100%), BTEX (up to 100%), PAHs (up to 100%), and total organic carbon (TOC) (96%–98%) [111].

As with other applications, the SiC treatment of oily wastewaters suffers from membrane fouling. In general, membranes with small pores are fouled by the formation of a cake layer, as oil droplets are retained and deposited on the membrane surface, whereas membranes with

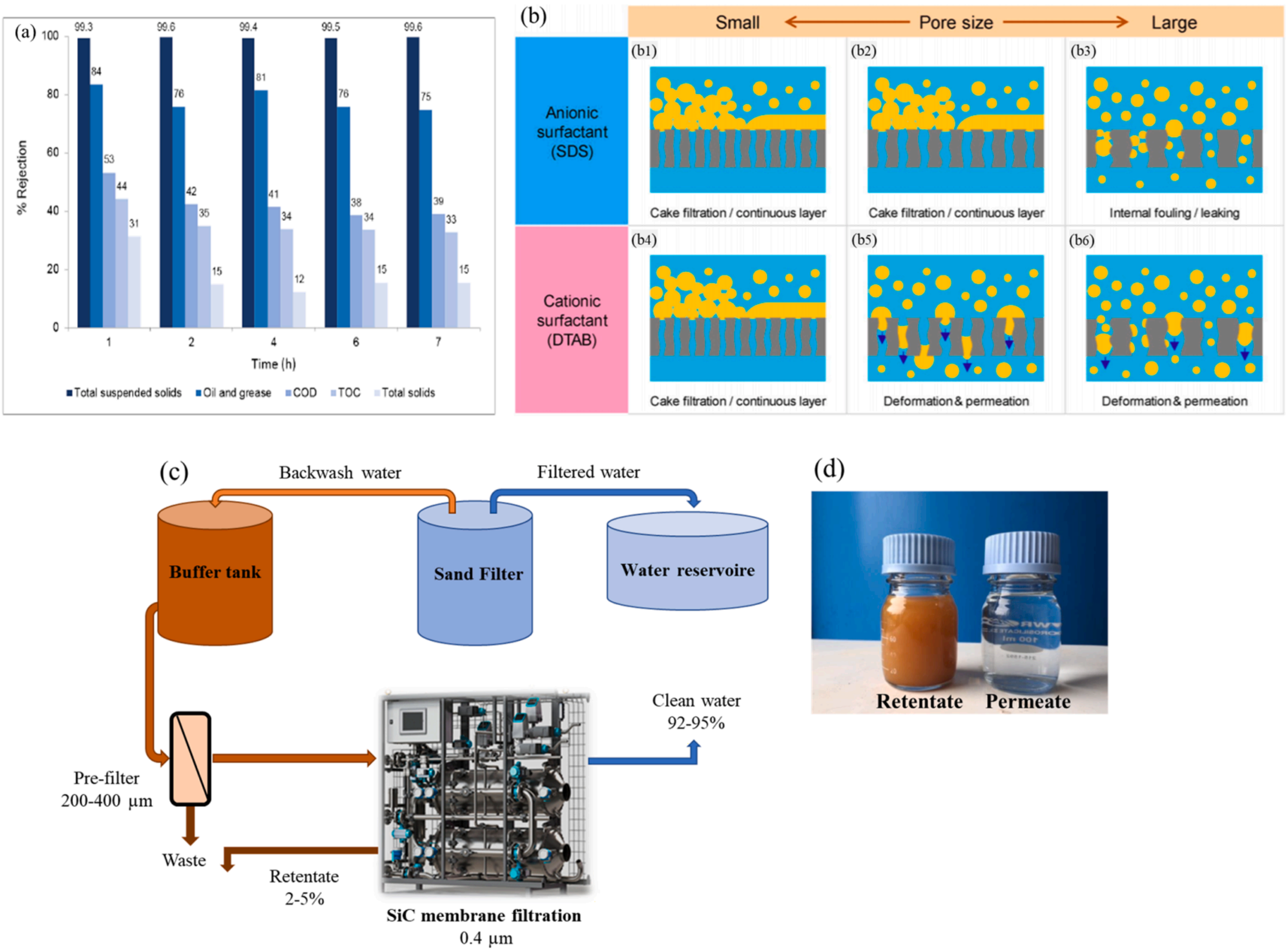

Fig. 6. (a) Rejection of TSS, oil and grease, TOC and COD in treatment of olive mill wastewater, adapted from [117]; (b) illustration of fouling of SiC membranes by oil in presence of anionic and cationic surfactants, adapted with permission from Ref. [123]. Copyright Elsevier 2020.; (c) process scheme for a system to recover water from sand filter backwash; (d) Permeate and retentate samples from MF of backwash water.

larger pores the same size as (or larger than) the oil droplets suffer from pore blocking [123]. In this case, fouling depends more on the surface charge interactions between the oil and the membrane, as illustrated in Fig. 6b. If the membrane and oil droplets have the same charge (anionic), oil droplets are repelled from the membrane surface and retained; hence, a fouling layer is formed near the membrane surface [123]. If, however, the oil droplets and membrane have opposite charges, the oil droplets can deform and enter through the pores, resulting in high water flux but poor oil retention. The rate of fouling also depends on the flux (hence indirectly on the TMP), as a higher flux promotes faster accumulation of oil droplets near the membrane and a higher chance of adsorption and blocking of pores [123]. Hence, in order to limit fouling and ensure high retention, it is crucial to ensure that the emulsions are stable. This has been demonstrated by Virga et al. [124] and Shi et al. [125], who have shown that high retention and low fouling can be obtained by tuning ionic strength and by surfactant addition. To limit fouling, it is recommended to operate at a sustainable flux or TMP, which can be determined by TMP or flux step experiments and, to enhance crossflow velocity [126].

3.2.2. *Sand filter backwash water recovery*

Another application of SiC membranes for wastewater treatment is the recovery of backwash water. The recovery of backwash water from sand filters has been demonstrated by the use of commercial membranes at an industrial dairy site (Arla Food Ingredients). The backwash water from sand filters is characterized by a high content of suspended solids—mainly iron oxides (ochre) and manganese oxides—and, potentially, organic matter. Fig. 6c shows a block diagram of the process, showing that the backwash water is prefiltered with a 200–400 µm prefilter before being treated with SiC crossflow MF. The system successfully removed the total suspended solids (99.9%) in the feed stream, and the TSS content in the feed stream (660 mg/L) was reduced to 0.7 mg/L in the permeate. Samples of retentate and permeate are shown in Fig. 6d. The total microbial load of the feed stream was also successfully reduced from 275 CFU/mL in the feed to 61 CFU/mL in the permeate, which is well below the accepted levels of 200 CFU/mL for drinking water. In addition, SiC membrane filtration was shown to efficiently remove heavy metals from the feed stream.

3.2.3. *Membrane bioreactors*

MBRs are becoming increasingly widespread for wastewater treatment, as they have advantages in comparison with conventional activated sludge (CAS) processes in that they allow the independent operation of the biological treatment and separation process. In the CAS process, organic matter is degraded and nutrients are removed in microbial processes, which are followed by sedimentation to produce a clear supernatant for discharge and sludge. In MBRs, membranes are integrated into the bioreactor. The membrane ensures high permeate quality, ideally free of bacteria. In addition, the filtration solution is less space consuming than the sedimentation process, and the rate of filtration can be increased, resulting in a more flexible operation that makes it possible to increase the flow through the wastewater treatment system without flushing out the microorganisms. Polymeric membranes currently dominate the market, as they have a lower cost, but ceramic membranes offer a longer lifetime and have therefore been investigated for application in MBRs [127]. Therefore, Cembrane has developed and commercialized MBR modules of immersed flat “hollow” sheets of SiC membranes that draw water from the sludge under a vacuum and produce a clean effluent. A recent study examined the treatment of synthetic industrial wastewater with tubular ceramic membranes coated with SiC [118]. As with other MBR processes, the membranes were scoured with air to prevent fouling. Membranes coated with SiC showed a higher removal of COD (94%) compared with uncoated membranes (87%), which was explained by the lower pore size of the SiC-coated membrane (0.5 μm vs. 1.5 μm). The initial flux declined from 235 LMH and 128 LMH to reach a steady-state fluxes of 50 LMH and 20 LMH for uncoated and coated membrane, respectively. However, membrane cleaning efficiently restored permeability.

Another promising application of SiC membranes is anaerobic MBRs (AnMBRs). Compared with polymeric membranes, ceramic membranes can be operated with higher TSS and volatile suspended solids (VSS) concentrations, as they are less prone to fouling and a higher shear can be applied to avoid fouling [119]. Operation at high VSS concentrations ensures high methane production, which can be obtained with membrane filtration while ensuring low hydraulic retention time (HRT). Accordingly, Cho et al. [119] operated an AnMBR treating domestic and food wastewater with a stable flux of 10 LMH and a methane productivity of 0.094 ± 0.069 L CH_4 g^{-1}.

3.2.4. Wet scrubber process water

Exhaust from marine engines must meet regulations from the International Marine Organization (IMO); as a solution, the exhaust can be passed through a scrubber [128]. In closed-loop wet scrubber systems, the water will absorb sulfur oxide particles along with, for example, heavy metals and must be cleaned before reuse or discharge into the sea. To this end, sophisticated systems with both pre- and post-filtration can be utilized. One example exploiting SiC membrane technology is explained in the following example, and illustrated in Fig. 7.

Engine exhaust is treated in a wet scrubber, where it is washed with water that thereby becomes contaminated. The water flow is recirculated from a process tank, from which a bleed-off is led to a water treatment unit (WTU) containing SiC UF membranes. Before filtration, there are several potential prefiltration options, including coagulation, pH adjustment, hydrocyclones, flocculators, or centrifuges [129]. In this example, the bleed-off process stream (WTU feed) first meets a break tank, followed by coagulation and/or flocculation and a pH-adjustment step in which a coagulant such as $FeCl_3$ or $AlCl_3$ is dosed along with, for example, NaOH to adjust the pH to an optimum value for coagulation (ranging from 7.5 to 9.5) [104,130]. The main purpose of the coagulation as a pretreatment in this setting is to increase the size of smaller particles that have a high potential for fouling the SiC membranes. In addition to increasing the size of the particles, which makes the particles less likely to pass through or foul the membrane, coagulation also targets heavy metals, including those in the particles that will be retained [131]. The coagulated feed water then passes through the next pretreatment step, such as a centrifuge or hydrocyclone. This step reduces the TSS and levels out peaks in the TSS to protect the membranes. Wastewater from the pretreatment is directed to the post-treatment, while the pretreated feedwater is treated by a crossflow UF SiC membrane unit with periodical backwash and CIP for membrane cleaning. Sludge produced from backwash is passed to post-treatment along with the crossflow loop retentate, while waste from chemical CIP is recirculated back to the process tank and treated again. Pretreatment waste, backwash sludge, and retentate from the filtration are combined in a sludge tank and flocculated by polymer addition. The sludge is then dewatered in a filter press, and the dry cake is stored for disposal. Reject water from the dewatering is returned to the process tank to be treated again [128].

3.3. Water treatment

3.3.1. Drinking water and backwash water from sand filters

Due to its high permeability and low footprint, SiC has the potential to replace sand filters in treating low-turbidity water, such as in drinking water treatment and the treatment of pool water. Membranes have advantages over sand filters in the relatively low volume required for backwashing, as sand filters require approximately 10% of the filtrated water for backwashing, which produces large amounts of dirty backwash water to be handled, corresponding to a 5%–10% water loss. Therefore, filtration with SiC membranes may replace sand filters; alternatively, SiC membranes can be installed to treat the large amounts of backwash water being produced every day at waterworks [113]. With low concentrations of suspended solids, MF membranes can be operated in semi-dead-end mode. Mueller et al. [113] showed that SiC membranes with mean pore sizes of 0.5 μm can reduce the particle counts in filtrate to values below the requirements for drinking water. However, after backwash, there are no protective fouling layers, which results in high particle counts in the permeate during the first minutes after backwash. Compared with a 0.01 μm polymeric membrane, the SiC membrane had less fouling formation, which was explained by the SiC membranes adsorbing less polysaccharides [113]. The lower fouling potential of SiC membranes in comparison with polymeric membranes has also been observed during the treatment of surface water. Fig. 8a presents the amount of reversible and irreversible fouling developed during filtration of surface water using different ceramic and polymeric membranes. The figure clearly show that SiC and TiO_2 membranes are less prone to reversible and irreversible fouling compared with polymeric, Al_2O_3, and ZrO_2 membranes [114].

3.3.2. Heavy metal removal

In industrial and academic contexts, SiC membranes are being developed and applied for the removal of heavy metals from drinking water and wastewater. Again, their high permeability, as well as their chemical robustness, make SiC membranes appropriate to treat harsh chemical waste streams. Heavy metals can be removed from wastewaters in the mining industry, anodizing industry, flue gas condensates, and so forth [132]. The reclamation of heavy metal ions may also facilitate the recovery and reuse of valuable rare earth materials.

In the removal of heavy metals from drinking water, the metals are first coagulated, for example by the addition of coagulant or by oxidation (by the aeration or addition of NaOCl oxidant). Coagulation allows the metals to be retained by MF membranes rather than requiring expensive and energy-consuming nanofiltration. For the treatment of groundwater containing arsenic, Gruppo Zilio S.r.L. has proposed the process outlined in Fig. 8b, combining oxidation, flocculation and MF before reverse osmosis (RO) and ion exchange [115]. It was demonstrated that the combination of oxidation with NaOCl followed by MF with a pore size of 500 nm can reduce the concentration of arsenic from 99 mg/L to 2 μg/L in drinking water [115]. During the MF filtration process, the flux was kept stable in the range of 400–600 LMH with a TMP of 0.25 bar by applying frequent backwashing.

3.3.3. Pool water treatment

For pool water filtration, MF membranes are used commercially for removal of bacteria and viruses. Skibinski et al. [116] studied the use of an MF SiC membrane with a mean pore size of 350 nm. Recirculating pool water was treated with surrogate colloids (50 and 500 nm microspheres and MS2 bacteriophages) to resemble bacteria and viruses. Filtration experiments showed that the removal rate of surrogates was positively affected by the salts in the pool water, leading to agglomeration and higher retention. Over 150 min filtrations, the removal rates for larger colloids increased due to pore blockage. Although retention was not complete, the removal performance still exceeded that of conventional sand filters without coagulation.

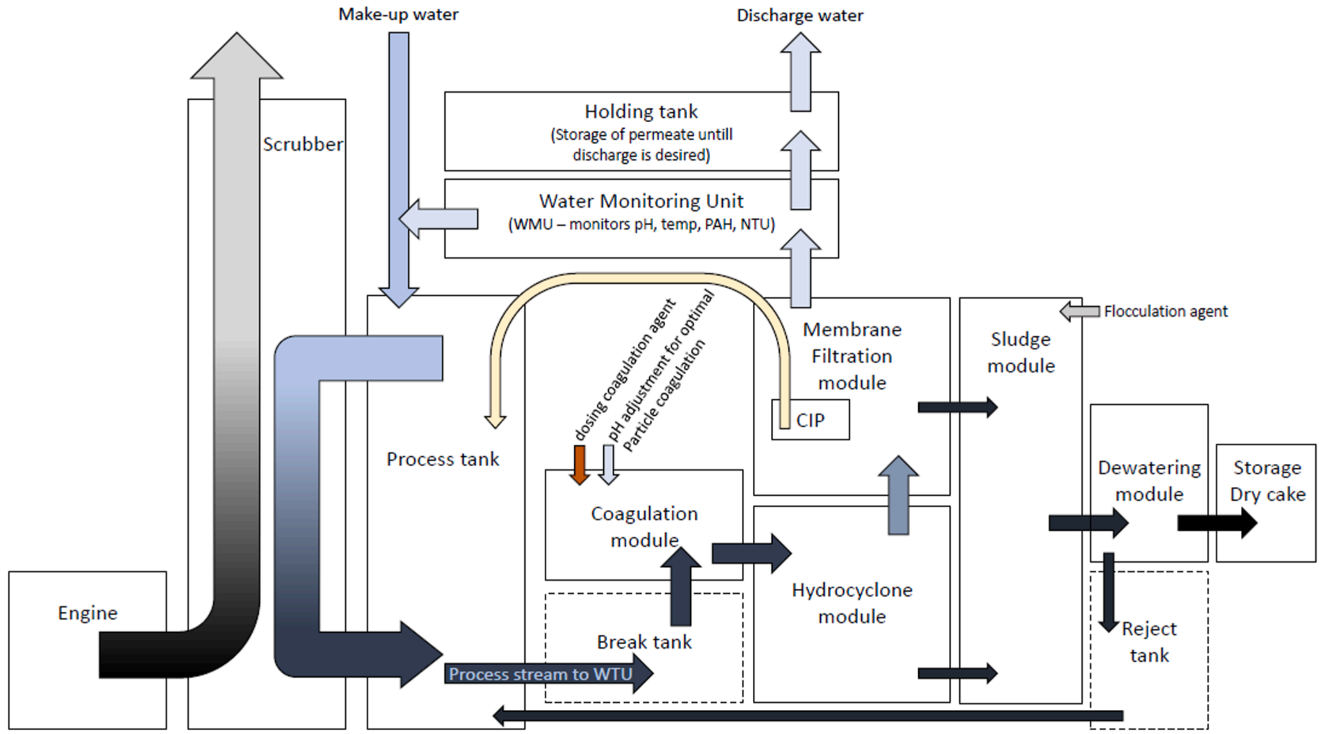

Fig. 7. Block diagram of LiqTech Water A/S SiC membrane crossflow filtration in a marine scrubber setting.

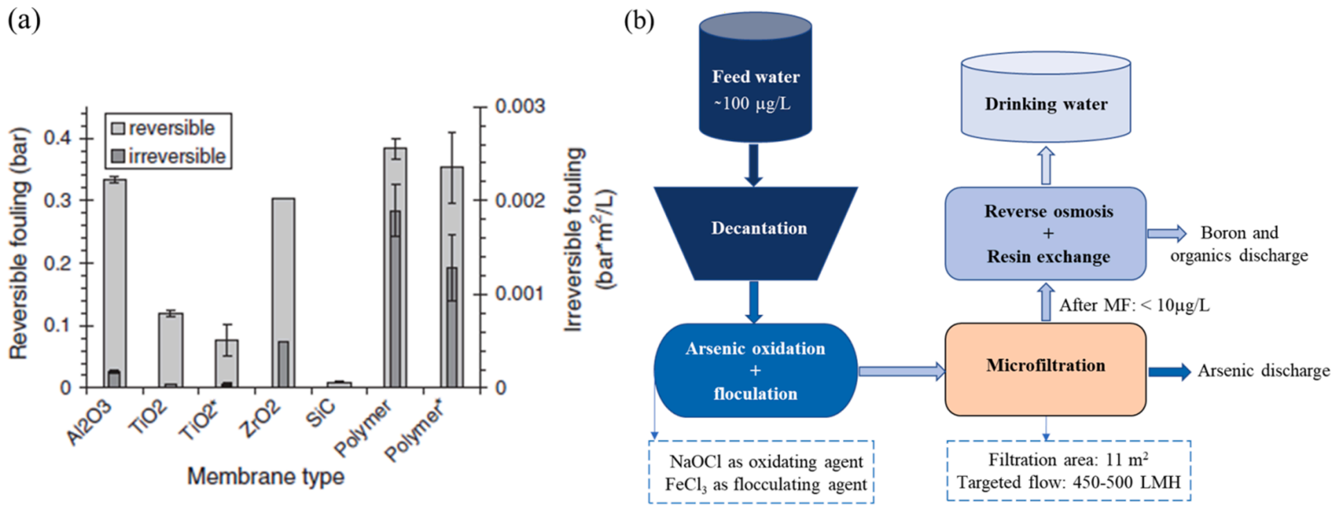

Fig. 8. (a) Amount of reversible and irreversible fouling developed during filtration of surface water. Adapted with permission from Ref. [114]. Copyright Elsevier 2011. and (b) process scheme for the treatment of groundwater containing arsenic, modified with inspiration from Ref. [115].

3.3.4. *Pretreatment before reverse osmosis*

Water is conventionally pretreated by UF or MF before being treated by RO, mainly to reduce the stress on the RO membranes and reduce fouling. SiC membranes have proven their potential for this purpose, as they offer high permeability and leave a high-quality effluent to be handled by the RO membranes. This potential has been demonstrated by treating seawater by UF filtration using SiC membranes prior to desalination by RO, which successfully reduced the amount of bacteria and colloids to reduce biofouling and maintain performance [133]. SiC UF membranes are also being used for the pretreatment of brackish water. Well water is pretreated by H_2S removal and coagulation before UF with flat-sheet SiC membranes to remove particulates and colloids of iron oxides, silt TOC, and bacteria. This is followed by RO for drinking water production [134,135]. Similarly, SiC membranes can be used for the pretreatment of flue gas condensate in power plants before RO treatment [136]. Again, efficient filtration in this situation depends on the coagulation of heavy metals prior to UF treatment.

3.4. *Food and biotechnology*

SiC membranes have been making inroads into food and biological applications and have recently been certified for use in the food industry [137,138]. This section describes the (few) recent applications in the food and biotechnology fields including fish proteins and microalgae recovery, beer clarification, and implementation with enzymes.

3.4.1. *Fish proteins*

Due to their chemical and thermal stabilities, SiC membranes can be an effective filtration media for recovering fish proteins. For example, Osman et al. [137] investigated the performance of SiC UF membranes in filtering two herring spice brines for the recovery of biomolecules such as proteins, fatty acids, and minerals for fishmeal (feed). The retentates contained 75%–82% of the protein and 75%–100% of the fatty acids from the initial feed stream brines. The fat (amino acids) was fully recovered in the retentate; however, the recovery of the phenolic compounds ranged from 0 to 39%. The results obtained in this study demonstrate that SiC UF membranes can recover biomolecules from marinated herring brines, although optimization of the pretreatment process is required.

3.4.2. *Microalgae harvesting*

In recent studies, SiC membranes have also been applied to microalgae harvesting [120,139–141]. Microalgae harvesting is a promising source of bioactive ingredients, such as polyunsaturated fatty acids, pigments, vitamins, and peptides. Fig. 9 shows a conventional process for producing microalgae powder. The biomass (TSS 0.5–1 g/L) was cultivated on industrial wastewater from Novozymes factory in Kalundborg (Denmark) and treated with MF to for a slurry (TSS 50–70 g/L) followed by centrifugation to form a paste (200–300 g/L) and finally drying the paste to form a powder [141]. Several microalgae species including *Monodopsis subterranea*, *Nannochloropsis salina*, *Dunaliella salina, Phaeodactylum tricornutum*, *Chlorella vulgaris*, *Chlorella sorokiniana*, *Chlorella pyrenoidosa*, *and Desmodesmus* sp. have been evaluated [139,140]. In these harvest performance studies, *Arthrospira platensis* [141], *Microcystis* sp. [120], and *Dunaliella salina* [142] exhibited a unique and identical flux pattern, while the performance of the harvest was found to be highly species dependent. The cell recovery efficiencies were higher than or equal to 98% for all microalgae species, and no cell rupture was observed. The filtration volume concentration ratio varied between 10 and 30, depending on the microalgae cell size, shape, and other parameters. In a field trial carried out for the harvesting of *Dunaliella salina* using a SiC membrane with a pore size of 1 μm, a total cell loss to the permeate of 3% was observed [142]. *Dunaliella salina* is a relatively big microalgae with no cell wall; thus, the filtration process can damage the cell. The dry-wet percentage was increased to 10% with a stable flux of 200–250 LMH and a concentration factor of 6. These findings provide support for the assumption that SiC membrane filtration can be a robust and reliable method for the downstream processing of microalgae. Ljubic et al. [141] found that MF with a 3 μm SiC membrane may cause moderate cell damage to *Arthrospira platensis*, while applying MF followed by centrifugation resulted in severe cell damage. *Arthrospira platensis* has a spiral shape of multicellular cylindrical filaments in an open helix with a length from 0.3 to 1 mm. Due to this large size and fragile cellulose-free cell wall, *Arthrospira platensis* is sensitive toward external stress.

Park et al. [120] studied the SiC membrane fouling mechanism in algal-rich water. The relationship between the fouling mechanism and different levels of coagulant was investigated as a measure of filtration resistance through a constant flow operation mode. The study showed that a certain amount of coagulant may reduce the filtration resistance, whereas the filtration resistance irreversibly increased when the coagulant dosage was above optimum levels. In a recent study, Kim et al. [143] reported an extremely low tendency of fouling by algal substances for SiC membranes due to their high hydrophilicities and negatively charged surfaces. During the filtration of an artificial feed stream with high concentrations of algae (*Chlorella* sp.), the SiC membrane was able to operate at a very high flux (150 L m^{-2} h^{-1}) compared with a polymeric membrane (5 L m^{-2} h^{-1}) under the same process conditions. These findings indicate that the SiC membrane filtration is a practical and feasible technique for microalgae harvesting and concentration. Moreover, a SiC MF system was also used to remove microorganisms, solids, and debris from growth media for microalgal growth. With the use of 0.4 μm SiC MF membranes, coliform, E-coli, and colony-forming units in the growth media were reduced by 99.88%, 99.59%, and 99.97%, respectively [144].

3.4.3. *Beer clarification*

Another application of SiC membranes in the food and beverage industry is beer clarification. Beer clarification can be a critical stage of the brewing process, since it is required to reduce the turbidity of the finished product caused by lactic bacteria and yeast. Saint-Gobain commercially demonstrated the use of a recrystallized SiC (R-SiC) membrane for clarification and stabilization (yeast and lactic bacteria removal) purposes, and found that the R-SiC membranes could keep a permeate flux of 50–100 LMH while ensuring a log removal value of yeast >4 [145]. The R-SiC membrane has been successfully tested in a series of pilot-scale studies on beer (0.25 μm), wine (0.6 μm), and coconut milk (0.25 μm and 0.6 μm).

3.4.4. *Industrial biotechnology*

Studies have also shown promising performances of SiC membranes in industrial biotechnology applications. For example, SiC membranes can serve as stable substrates for covalent enzyme immobilization. This has been demonstrated by treating membranes with NaOH to form hydroxyl groups on the SiC membranes in order to covalently bind the enzyme alcohol dehydrogenase (ADH). The functionalized membrane could then be used in a membrane catalytic reactor to continuously produce methanol from formaldehyde [146]. In general, ceramic SiC

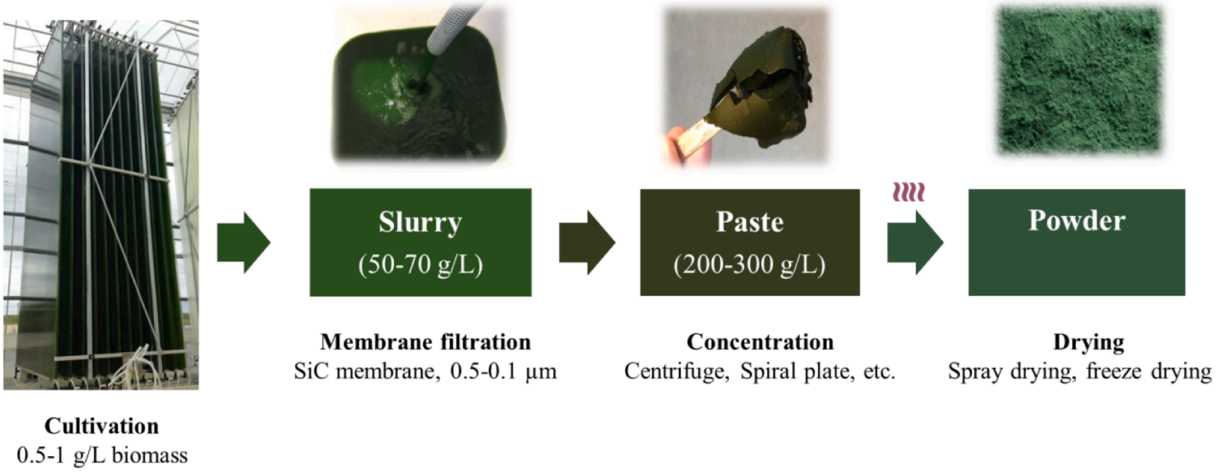

Fig. 9. Downstream processing of microalgae involving biomass cultivation, MF, centrifugation, and drying to form a powder of microalgae.

membranes are expected to have significant potential for industrial biotechnological applications, as they can withstand harsh conditions, such as those in fermentation and biorefining.

3.5. SiC membrane cleaning methods

SiC membranes are conventionally cleaned by physical and chemical cleaning. Physical cleaning covers backwashes, such as the reversal of flow through the membrane, and air scouring during relaxation, such as a break in permeation during which there is no transport of foulants to the membrane. The latter is primarily used in membrane bioreactors. In addition, the mechanical stability of ceramic membranes enables backwash at higher fluxes (3000–9000 LMH) with higher efficiencies than conventional polymeric MF backwash fluxes (200–300 LMH) [113]. In addition, the high physical robustness of ceramic membranes allows for cleaning with back-pulsing or back-hammering [147]. During back-pulsing, compressed air is introduced through the permeate line and is pressed through the membrane to remove fouling deposits and unblock pores. In addition, applying a high crossflow velocity during filtration is beneficial, as it prevents larger particles from depositing onto the membrane to block a pore [148]. However, it should be noted that applying high crossflow velocities is expensive, as it is energy consuming and requires large crossflow pumps. Therefore, the trade-off between fouling reduction and energy consumption should be investigated for each specific application. In addition, crossflow results in a selection of particles, as larger particles are removed more easily than smaller (colloidal) particles. Hence, at higher crossflow velocities, it is mainly smaller particles that deposit on the membranes to form dense cakes or to block the pores of the membrane [148].

Chemical cleaning is conventionally carried out using acids and chelating agents to remove mineral deposits (scaling) and alkaline cleaning agents in combination with surfactants and oxidizing agents, such as NaOCl, to remove organic fouling, such as biofilms [44]. For cleaning under milder conditions, enzymes have also shown promise for degrading organic fouling layers, such as biofilms. Polymeric membranes are often limited to cleaning temperatures of 40–45 °C, whereas ceramic SiC membranes can be cleaned at higher temperatures and within a broad pH interval of 0–14. The high chemical resistance of SiC membranes enables the application of harsher cleaning methods, such as ultrasonic cleaning and ozonation. Alresheedi et al. [45] studied the effect of ozonation and compared it with conventional NaOH and NaOCl cleaning. They found that ozonation is more efficient (less time-consuming) and less expensive than conventional cleaning. Ultrasonic cleaning is also an emerging technique for fouling control and membrane cleaning, as presented in a recent review article [149]. Alternative approaches are also being developed, such as electrochemical degradation of fouling layers on electrically conductive membranes [150] and functionalized membranes (e.g., photocatalytic) for the degradation of organic fouling layers [151]. Furthermore, Lohaus et al. [152] investigated the direct joule heating of SiC membranes to control fouling and showed that fouling resistance was reduced by up to 30% compared with regular backwash. Another way to clean SiC ceramics is by air nanobubbles, as the collapse of nanobubbles leads to the formation of reactive oxygen species, which are able to degrade organic fouling layers [153]. This effect has been demonstrated on SiC membranes fouled with humic acids and showed the complete removal of fouling and the restoration of flux.

Finally, a key strategy to reduce membrane fouling is to monitor and control the feedwater quality; that is, reducing feedwater TSS by filtration or centrifugation reduces the load on the membrane. Coagulation is also a common pretreatment before membrane filtration, as it efficiently removes smaller colloids that can potentially block membrane pores irreversibly [154,155].

4. Commercialization of SiC membranes

Extensive research has been done on SiC membrane fabrication and technology to enable the commercialization of SiC membranes. At present, several types of SiC membranes with different configurations (e.g., tubular, flat-sheet, and disc) and characteristics (e.g., pore sizes, diameters, and length), which make them suitable in different applications, are commercially available. Table 4 presents these products in respect to producer, product name, geometry, dimensions/membrane area, features, and applications. The main SiC membrane providers in the market are LiqTech Ceramic A/S (Denmark), Alsys Group (France), Saint-Gobain Performance Ceramics & Refractories (Germany) and Cembrane A/S (Denmark). Fig. 10 shows some examples of commercially available SiC membrane products in tubular (Fig. 10a, 10c, and 10d), flat-sheet (Fig. 10b), and disc (Fig. 10e) configurations. Multi-channeled tubular and flat-sheet SiC membranes assembled in a membrane module are also demonstrated in Fig. 10a and 10b, respectively. Multi-channeled tubular SiC membranes dominate over other geometries in large-scale water and wastewater treatment applications, since they provide a higher filtering surface/volume ratio. In addition to membrane geometry, membrane module design is a crucial parameter for providing an increased membrane filtration area. For example, the membrane module developed by LiqTech Water A/S (Fig. 10a) combines 99 multi-channeled SiC membranes, resulting in an increased specific filtration area. SiC flat-sheet membranes are generally used in immersed units such as MBRs. As shown in Fig. 10b, several SiC flat-sheet membranes have been sandwiched together by CERAFILTEC (Germany) to form a membrane module. This module arrangement is useful for potential applications due to its easy membrane cleaning and replacement. On the other hand, the low packing density of SiC disc membranes increases the footprint; therefore, their large-scale application is rather limited. Thus, the ceramic industry should devote more effort to the optimization and improvement of SiC disc membrane configuration.

At present, commercially available SiC membranes are positioned in the MF/UF market segment. The pore sizes of commercial SiC membrane for UF are in the range of 1–100 nm, whereas the pore sizes of SiC membranes for MF are >100 nm. Regardless of the producer, commercial products with high permeability, stable flux, and good rejection of particles have been widely applied by the water and wastewater treatment industries, especially for MF applications. Although the industrial-scale production of SiC membranes has been a well-developed technology for decades, the manufacturing of membranes with a smaller pore size and narrower pore size distribution is the main challenge to be overcome in order to provide solutions to current challenges in water and wastewater treatment, such as in NF applications.

As indicated previously, the membrane market for water and wastewater treatment is dominated by polymeric products (around 90%). Industrially applicable commercial polymeric membranes cost around 50–200 USD/m^2, whereas the price of ceramic membranes is 500–1000 USD/m^2 [156]. Despite the reduced operational and maintenance costs of ceramic membranes (due to their longer lifetime and stronger mechanical properties in comparison with polymeric membranes), their high capital cost (due to the material cost and thermal treatment) limits their acceptability over polymeric membranes. For several years, it was expected that ceramic membranes would be able to narrow the gap, thanks to efforts by the ceramic industry to reduce their capital costs, such as through optimization of the design of membrane modules, optimization of operating conditions, the use of low-cost raw materials, and the development of cheaper fabrication techniques. Indeed, these recent technical and commercial developments have helped to reduce the cost of ceramic membranes in the last decade [157]. However, it has been difficult for ceramic membrane producers to reduce the cost further, due to an absence of economies of scale. Nevertheless, cost reduction can be achieved if the number of ceramic membrane implementations increase, especially for large-scale systems. All things considered, once the ongoing efforts toward decreasing the

Table 4
The properties of commercial SiC membranes from membrane companies.

Company	Product Name	Geometry	Dimensions/Membrane area	Features	Applications
LiqTech Ceramics A/S, Denmark	COM0250305xxx-03	Multichannel tubular & Monotube	OD[1] = 25 ± 1 mm L[2] = 305 ± 1 mm CD[3] = 3 mm Area = 0.09 m^2	• Pore size: 0.1–1 μm • pH range: 0–14 • Operating pressure: max 10 bar TMP[4] • Temperature tolerance: up to 800 °C	• Marine scrubber wash water • Produced water • Prefiltration for RO[5] • Industrial wastewater • Pool and spa water • Oil emulsion separation
	COM0251016xxx-03	Multichannel tubular & Monotube	OD = 25 ± 1 mm L = 1061 ± 1 mm CD = 3 mm Area = 0.28 m^2		
	COM0251178xxx-03	Multichannel tubular & Monotube	OD = 25 ± 1 mm L = 1178 ± 1 mm CD = 3 mm Area = 0.33 m^2		
	FSM500100UF-22	Flat-sheet Disc	L = 500 ± 2 mm W[6] = 100 ± 1.5 mm T[7] = 6 ± 1.0 mm Area = 0.106 m^2 OD = 374 mm ID[8] = 25/91/131 mm T = 4–10 mm	• Flux: >3000 LMH (@ 25 °C-ultra pure water@1 bar) • Pore size: 0.2 μm/1 μm	• Wastewater treatment and reuse • Ground water • Drinking water • Prefiltration for RO • Landfill leachate • Galvanic wastewater • Oil sludge • Algae concentration
ALSYS Group, France	CeraMem®	Multichannel tubular	D[9] = 142 mm L = 864 mm CD = 2 mm Area = 10.5 m^2	• Nominal pore size: 0.2 μm for MF[10] and 50 nm for UF[11] • pH range: 0–14 • Maximum temperature: ≥130 °C • Maximum TMP: 10 bar • Recommended crossflow velocity: 2–3 m/s • Volumetric flow rate for 2 m/s: 50 m^3/h	• Produced water • Wastewater treatment and recovery • MBR[12] • Water treatment • Solids removal from chemical streams
	CeraMem®	Multichannel tubular	D = 142 mm L = 864 mm CD = 5 mm Area = 5 m^2		
Cembrane A/S, Denmark	SiCFS-0175-DO-T-599	Flat-sheet	L = 615 mm W = 150 mm T = 6/12 mm Active membrane surface: 0.1752 m^2	• Pore size: 0.1 μm • pH range: 1–13 • Max. permeate flow: 300 L/h • Maximum backwash pressure: 2 bar • Operating temperature: 5–60 °C	• MBR • Drinking water • Municipal Wastewater • Industrial Wastewater
Saint-Gobain Performance Ceramics and Refractories, Germany	Crystar® FT250 Crystar® FT600 Crystar® FT1000 Crystar® FT3000	Multichannel tubular Multichannel tubular Multichannel tubular Multichannel tubular	OD = 10 mm L = 400 mm CD = 6 mm Filtration area: 0.018 m^2/m OD = 25 mm L = 1178 mm CD = 17 mm Filtration area: 0.053 m^2/m OD = 25 mm L = 1178 mm CD = 3 mm Filtration area: 0.3 m^2/m OD = 41 mm L = 1200 mm CD = 3 mm Filtration area: 0.76 m^2/m	• Pore sizes:250–3000 nm • Chemical resistance:0–14 pH value • Porosity: ≥40% • Max. application temperature: < 1000 °C (in air)	• Food and beverage clarification • Biotechnology processes • Chemical recovery • Water and wastewater treatment • Oily wastewater • Prefiltration for RO

All information was taken from companies' websites.

[1] OD: outer diameter; [2] L: length; [3]CD: channel diameter; [4]TMP: trans membrane pressure; [5] RO: reverse osmosis; [6] W: width; [7] T: thickness; [8] ID: inner diameter; [9] D: diameter; [10] MF: microfiltration; [11] UF: ultrafiltration; [12] MBR: membrane bio reactor.

high capital cost of ceramic membranes (specifically SiC membranes) are combined with economies of scale, market acceptance of ceramic membranes will gradually increase.

5. Concluding remarks and future perspectives

SiC supports and membranes can be produced in different shapes and dimensions on an industrial scale by established ceramic processing technologies. Thanks to their outstanding robustness and water permeability, the use of SiC membranes has expanded over the last decades in an increasing number of industrial sectors, including oil and gas, water purification, wastewater treatment, and the processing of food and beverages. Moreover, the most recent advances in fabrication procedures, the use of sintering additives, precursor processing, and module design make it possible to address two important limitations of SiC membranes: namely, the production costs, which are still high compared to those of ceramic oxides and polymeric membranes, and the possibility of controlling the pore size in the UF and NF range [18,37].

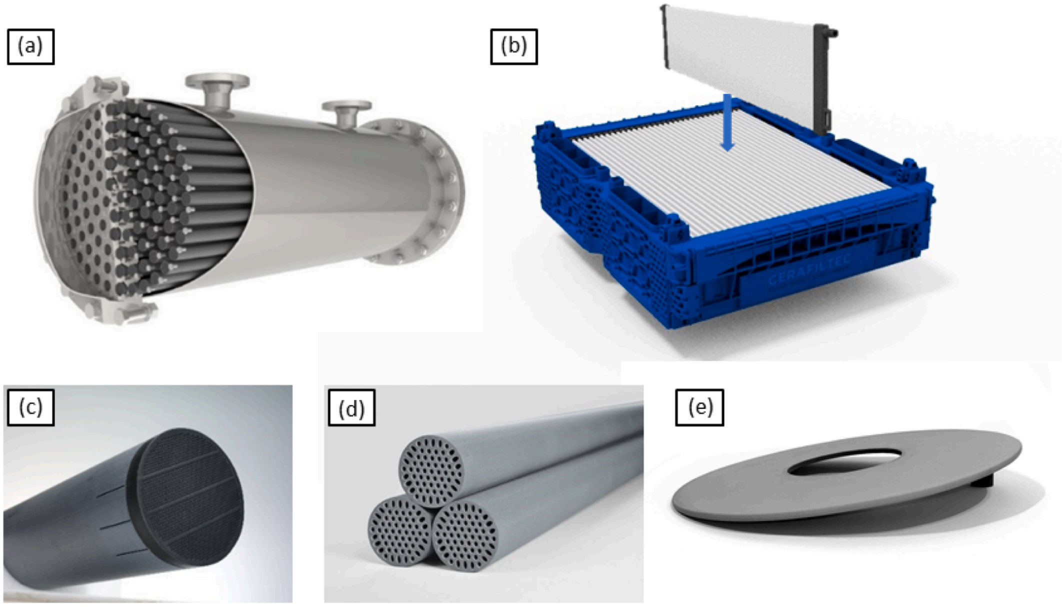

Fig. 10. Commercially available SiC membranes for water and wastewater treatment from: (a) LiqTech Ceramics; (b) CERAFILTEC; (c) Alsys; (d) Saint-Gobain Performance Ceramics & Refractories; (e) LiqTech Ceramics. (Parts (a) and (c) reprinted under copyright permission by LiqTech Ceramics and parts (b–d) reprinted under copyright permission by CERAFILTEC, Alsys, and Saint-Gobain Performance Ceramics & Refractories, respectively.)

Due to these advancements, new applications for SiC membranes can be foreseen in the near future. The success of the green transition to produce chemicals and energy from biorefineries is largely limited by separation efficiency in the various processes, so there is great potential for the integration of membranes in different upstream and downstream processes, such as for process intensification in fermentation and enzymatic reactions. In such contexts, the SiC membranes benefit from high physical and chemical resistance under the harsh chemical and physical conditions of membrane-integrated fermentation processes. Finally, there is clear potential for the integration of inorganic SiC membranes with high permeability and a long lifetime for process intensification and the purification of products in the pharmaceutical industry.

Declaration of Competing Interest

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

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