The Application of Pressure-Driven Ceramic Membrane Technology for the Treatment of Industrial Wastewaters -A Review

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Abstract

This paper presents a review of the previous laboratory analysis and case studies on the application of the pressure-driven ceramic membrane technology for treatment of industrial wastewaters. Ceramic membranes has attracted remarkable interests in recent decades for industrial wastewater treatment because of their superior characteristic such as high fluxes , reliable working lifetime under aggressive operating conditions and ease of cleaning. The literature review revealed that the efficiency of this technology has been proven in a wide variety of wastewaters from different industries and activities including pulp and paper, textile, pharmaceutical, petrochemical, food and mining. However, there are still challenges and questions for this technology that need to be addressed in future researches such as investment cost optimisation by introducing new fabrication technologies, selectivity, permeability and packing densities improvement, fouling minimisation and proposing scale up based on experimental research results.

Keywords: Industrial wastewater, ceramic membrane, Microfiltration, Ultrafiltration, Nanofiltration

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1. Introduction

Generally, Industrial wastewater is an aqueous discharge due to the use of water or cleaning activities in an industrial manufacturing process [1]. Industrial activities generate wastewaters that varies so significantly in pollution characteristics, and each sector of industry produce its own combination of pollutants [2]. These industrial wastewaters may contain heavy metal ions, organic compounds, nutrients, colouring matters, pesticides, endocrine disruptive compounds, and some other toxic materials. As a result, these Industrial effluents should be efficiently treated to protect the environment, aquatic life and humans from intoxication. In addition, due to continuing increase in water shortages and environmental protection concerns, industrial effluent treatment for reuse in the process has been accepted as a sustainable option to address these problems [3].

Ceramic membrane-based treatment system is one of the emerging technologies of treating wastewater that have attracted remarkable interests for the industrial wastewater treatment over the past two decades. The ceramic unit has many benefits over polymeric membranes like high durability, superior chemical, mechanical and thermal stability, bacteria resistance, ability of back flushing and ease of cleaning and sterilization [4-6]. However, there are still challenges for this technology, particularly in optimising capital and fabrication cost, improving selectivity and antifouling properties, enhancing packing densities, and applying experimental research results to large-scale applications [7, 8].

This paper reviews the studies and investigations conducted on the application of pressure-driven ceramic membranes for the treatment of industrial effluents. The paper begins with a brief discussion about ceramic membrane materials and manufacturing followed by a review of the previous laboratory analysis and case studies about the efficiency of this system in the treatment of wastewaters from different industries. It also covers the challenges and future trends in ceramic membrane technology for industrial wastewaters filtration. Finally, the paper concludes with key findings and recommendations.

2. Ceramic Membrane Technology

2.1 Ceramic Membrane Materials

In terms of separation process, a membrane is described as a selective barrier to separate two phases and it can limit the transport of various elements [9]. There are different categories of membranes based on their materials, such as: 1) polymeric membrane 2) ceramics membrane 3) liquid membrane, and 4) ion exchange membrane [10]. Ceramic membranes for the purpose of wastewater treatment belong to the oxide ceramic membranes which are mainly made of Al, Si, Ti or Zr oxides, and silicon carbide (SiC) and covers the range from Microfiltration (MF) to Nanofiltration(NF). Different oxides have different performance and chemical and hydrothermal stability depending on the operational environment conditions, and therefore can be chosen based on the specific application requirements because each oxide has a different surface charge in solution [11-13].

Desired ceramic membranes for industrial effluent filtration are mainly porous asymmetric structures consisting of a porous support layer , intermediate layer(s) and a thin skin top layer with different densities depending upon the desired molecular weight cut off (MWCO) of the ceramic membranes. All layers can be made of the same material which is called integral or of different materials, which in this case is called composite ceramic membranes and both of them has been used for the filtration of industrial effluents. Figure 1 illustrates the scanning electron microscope(SEM) of the cross-section of a asymmetric composite ceramic membrane structure made from different materials [14].Composite ceramic membranes properties and selectivity can be customized by applying different materials in different layers; however, their fabrication process is multi-step and complex [11, 12, 15].

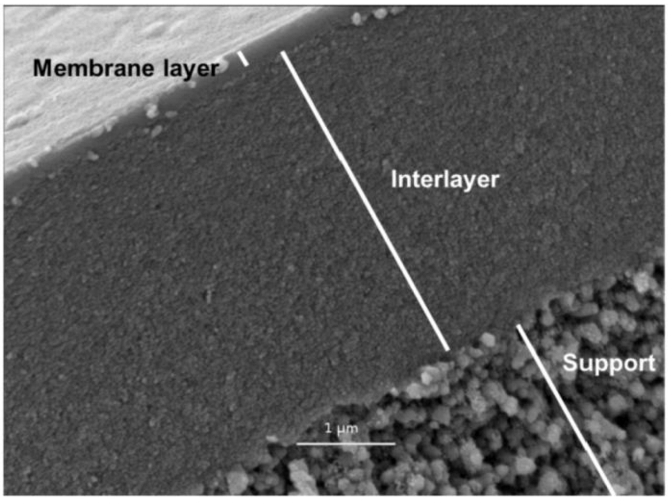

Fig 1. SEM of the cross-section of an asymmetric composite ceramic membrane (reproduced from [14] with permission from the Royal Society of Chemistry)

2.2 Ceramic Membrane Configurations and Their Fabrication Methods

2.2.1 Membrane Configurations

For practical applications, membranes need to be configured into packages that are called membrane modules. They provide a large surface area for an effective feed stream filtration [9]. Ceramic membranes are configured with either a flat geometry and/or cylindrical shapes and of different packaging, volume ratio and materials type to address different operational situations. For the purpose of industrial effluents filtration, cylindrical configuration with single and multi-channel tubes and hollow-fibres are more suitable because of easier sealing of the elements, higher mechanical stability, and better capability to handle higher cross -flow velocities compared to flat geometry [8, 12]. However, because of ceramic brittleness, optimising the packing densities of ceramic modules in order to reduce the overall footprint of installed treatment unit in operating environment is one of the main concerns of researchers and ceramic membrane manufacturers [12]. Figure 2 shows some photographs of commercially available flat sheet, tubular and hollow-fibre geometries for ceramic membranes.

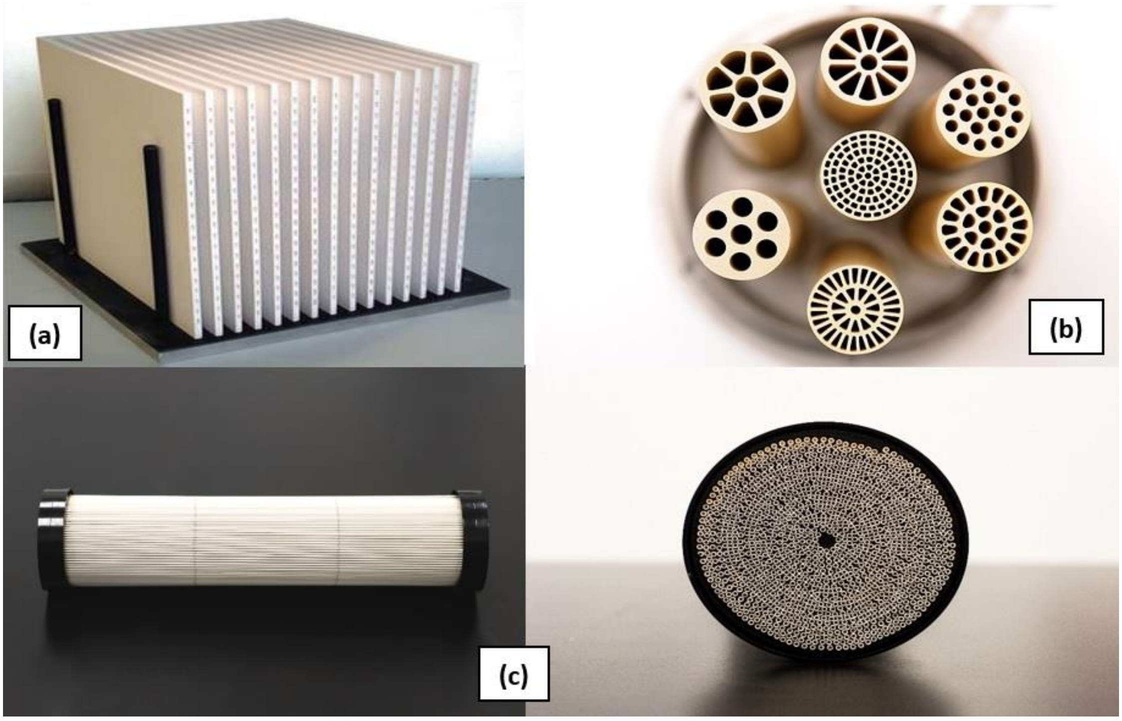

Fig 2.Product photographs of commercial (a) Flat-sheet membrane (reproduced from [16] by permission of © KERAFOL Keramische Folien GmbH), (b) Tubular ceramic membranes (reproduced from [17] by permission of TAMI industries) (c) Ceramic hollow–fibre Membrane (reproduced from [18] by permission of i2m manufacturing company)

In recent years, commercial ceramic membrane manufacturers have tried to improve the packing densities of ceramic membrane modules. Table 1 lists some current ceramic MF/UF/NF suppliers. Pall®Membralox® developed asymmetric multi-channel tubular alumina MF with pore sizes ranging from 0.1-1.4 µm and zirconia Ultrafiltration (UF) with pore sizes ranging from 20-100 nm in a unique hexagonal monoliths module to obtain a high packing density up to 240 m^2/m^3. However, large pressure drop for permeate flow across the monolith is a technical limitation that restricts the diameter of monoliths than can be used [12, 19, 20]. In order to address this problem, Veolia Water Technologies introduced the CeraMem® technology that effectively overcomes the pressure drop problem by mechanical modification to the monoliths. Multiple permeate conduits that conduct permeate through the feed passageways to the permeate collection zone at the end of module were added within the monolith [12, 21]. More recently, TAMI industries Introduced Isoflux ™ with flower-like tubular geometries of 8, 23 and 39 channels with membrane filtration area ranging from 0.2-0.5 m^2. This allows for a stable permeate flux on each point of the membrane independent on the position of measurement which can be beneficial for food processing and bio industry [22]. Hollow-fibre module utilizes tubes with small diameter generally between 2-4 mm thereby compact configuration with highly effective membrane filtration area can be obtained [12]. Furthermore, Fraunhofer IGB introduced a laboratory scale wet-spinning process for the production of porous asymmetric ceramic membranes in capillary module with the outer diameters ranging from 0.5 to 4mm which can improve the packing density of ceramic membranes in hollow-fibre configuration[23]. However, under real operational condition severe fouling and fibre breakage may occur [24]. In recent years, there have been a lot of research on packing density improvement of ceramic membrane modules where good results have been achieved. However, there still an ongoing requirement to design more space-effective modules by fabricating narrower hollow-fibres with an appropriate mechanical strength to reduce the ceramic membrane footprints as much as possible in large scale installation.

As mentioned earlier, ceramic membranes find frequent use in industrial wastewaters treatment, and different ceramic membrane materials and modules have been produced worldwide, and many investigations has been conducted to improve the packing densities of ceramic membranes. Yet, commercially available ceramic membranes are still proportionately more difficult to fabricate compared to polymeric membranes and their investment cost is higher than polymeric types. The usage of ceramic membranes has therefore been limited in many real industrial applications and polymeric membranes have dominated the industrial effluents treatment market for decades [25].

Table 1: Some Commercially available ceramic membranes for Industrial effluents filtration

Company	Product	Geometry	Designation	Material of Membrane	Pore size/ MWCO	Available Length(s)-(mm)	Number of Channels	Outer Dia (mm)	Channel Dia(mm)	Ref
TAMI Industries	INSIDE CéRAM™	Tubular	MF UF Fine UF	-	-	580, 850, 1020, 1178	7,8,11,19,23,25,37, 39,93	25,41	1.6,2.5,3.5, 3.6, 4.6,5.5,6	[26]
	Filtanium™	Tubular	MF UF Fine UF	-	-	580, 1178	8,23,39	25	2.5,3.5,6	
	Isoflux™	Tubular	MF	-	-	1020,1178	8,23,39	25	2.5,3.5,6	
	Eternium™	Tubular	-	-	-	1178	7,8,23	25	3.5,6	
atech Innovations GmbH	atech Ceramic membranes	Tubular	MF & UF	MF: α-Al_2O_3,TiO_2, ZrO_2 UF: TiO_2,ZrO_2,Al_2O_3	MF: 1.2,0.8,0.4,0.2,0.1 µm UF: 0.05 µm, 150,100,20, 10, 5, 1 KDa	1000,1200, 1500	1,7,19,37,61,85, 211	10,25.4, 30,41, 52,54	2,2.5,3.3, 3.8,4,6,8,16	[27]
Pall Corporation	Pall® Membralox® IC	Tubular (Hexagonal)	MF&UF	MF:α-Al_2O_3 UF: ZrO_2	MF:0.8,0.2 µm UF:100,50,20 nm	1020	48	38,43	4	[28]
Pall Corporation	Pall® Membralox®	Tubular (Hexagonal)	MF&UF	MF:α-Al_2O_3 UF: ZrO_2	MF:1.4,0.8,0.5, 0.3,0.1 µm UF:100,50,20 nm	1020	19,37	28,31 38,43	3,4,6	[29]

Table 1: Continued

Veolia Water Technologies	CeraMem®	Tubular	MF& UF	MF: mixed oxide, α-Al_2O_3,SiC,TiO_2 UF: SiC, SiO_2,TiO_2	MF:0.1,0.2,0.5 µm UF:0.01,0.005µm , 50 nm	864	-	142	2,5	[30]
ItN Nanovation AG	CFM Systems®	Flat sheet	MF	α-Al_2O_3	0.2 µm	L=530 W=6.5 H=110	21	-	3	[31]
Meidensha Corporation	Ceramic flat sheet membrane system	Flat sheet	MF	α-Al_2O_3	0.1 µm	L=1046 W=12 H=281	-	-	-	[32]
LiqTech International Inc.	CoMem® Conduit	Tubular	-	SiC	-	865	-	146	3	[33]
LiqTech International Inc.	CoMem®	Tubular	-	SiC	-	305,1016,1178	-	25	3	[34]
Inopor®	Ceramic inopor® membrane	Tubular	NF	Support Layer:Al_2O_3 Membrane Layers: TiO_2 or SiO_2	MWCO: 750 ,600,450 Da	1200	1,4,7,19,31	10,20, 25,41	3,3.5,6,6.1, 7,15.5	[35]
Cembrane	Cembrane Ceramic membrane	Flat sheet	MF	SiC	0.1 µm	L=532 W=11 H=150	-	-	-	[36]

2.2.2 Fabrication Techniques

Figure 3 shows the conventional multi-step process of fabrication of composite ceramic membranes. The choice of method in shaping, heat treatment, and layer deposition processes depends on the application and membrane configuration [11, 12, 15, 37]. One of the main difficulties associated with conventional fabrication processes is the strengthening of ceramic powders and suspensions which requires high sintering temperatures and long sintering times, where consequently grain growth and decomposition of ceramics may occur [38]. In recent years, The combined Phase-inversion and sintering technique has been used as an alternative method for producing wide range of ceramic membranes including flat sheet, hollow-fibre and tubular configurations [39-50]. This method has shown remarkable advantages over conventional methods. Firstly, it is known as one step fabrication process to produce asymmetric ceramic membranes because one heat treatment session is required. Secondly, due to formation of finger-like micro-channels associated with this technique, significant reduction in mass transfer resistance for permeation flux can be observed during operations [12, 48]. This technique consists of preparation of a suspension containing ceramic particles, organic solvent, polymer binder and water. Due to solvent/non-solvent exchange induced phase inversion process, solidification of ceramic suspension occurs and ceramic particles are immobilized by spinning or casting depends on required geometry. Finally, the membrane precursors formed with this method go through a one-step heat treatment to remove all organics and strengthen mechanical properties [12, 40, 50]. Current research has made remarkable progress in determining the effects of different parameters on final selectivity and mechanical strength of ceramic membranes produced by this method. Kingsbury et al. (2009), Tan et al. (2001) & Wei et al. (2008) found that the pore size and selectivity of the final membrane is highly affected by size distribution of ceramic particles in the suspension. They succeeded to achieve various MWCs in the range of hollow-fibre MF and UF by applying different alumina and zirconia particle sizes in the suspension. In addition, they realized that changes in ceramic to polymer binder ratio have different effects on the mechanical strength of the membrane [40, 44, 45]. Kingsbury et al. (2009) & Tan et al. (2011) studied the morphology of different asymmetric alumina hollow-fibres made by combined phase-inversion and sintering. Two basic sub-structures including finger -like and sponge- like have been observed within the membrane cross section. They found that by changing spinning process parameters including viscosity of the spinning suspension, bore fluid composition and flow rate, hollow- fibre morphology can be varied remarkably [40, 51]. On the other words, variation in spinning parameters leads to different dimensions of the finger-like and sponge-like sub-structures, consequently different morphologies will be generated.

As a result, combined phase-inversion and sintering technique has a great potential to produce ceramic membranes for industrial wastewater treatment applications. However, one of the main drawbacks of this technique is high sintering temperature which has an adverse effect on surface porosity and mechanical strength of resultant ceramic membranes. Advanced sintering methods such as Controlled sintering process by using polyethersulfone (PESf) as a pore structure stabilizer [46], microwave sintering [52-55], spark plasma sintering [56-59] and high frequency induction heat sintering [60-62] have been introduced for inhibiting grain growth during ceramic powder consolidation and for reducing the sintering process temperature and time. Despite remarkable advantages of these advanced sintering methods over conventional sintering techniques such as large energy saving, better grain distribution and enhanced mechanical properties of produced ceramics [52, 53, 55], controlling grain growth during sintering process is still a major issue, which makes nanostructured ceramics hard to fabricate [38]. Therefore, further investigations are still needed to introduce non-complex and economical fabrication methods with lower temperatures of sintering and shorter processing times to minimise the problem of grain growth, and makes the production of nanoceramics with lowest grain size possible.

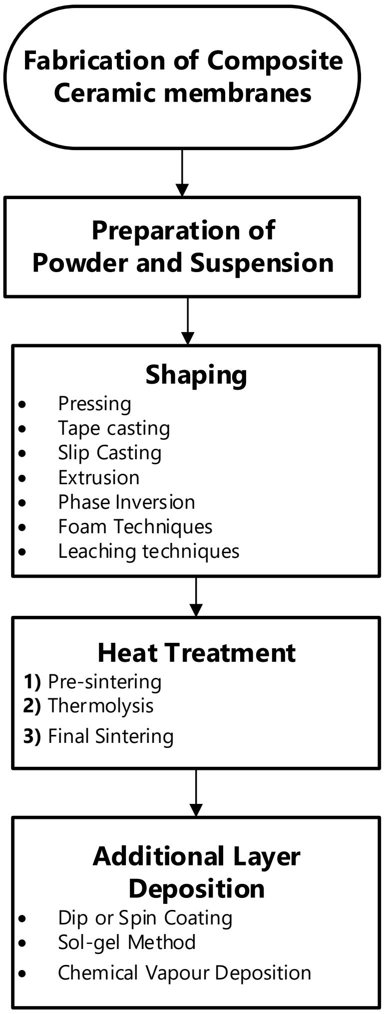

Fig 3. Conventional fabrication of composite ceramic membranes(Adapted from [12])

3. Application for the Treatment of Industrial Wastewaters

One of the most serious environmental issues in the world is the existence of harmful and toxic pollutants in industrial wastewaters. The major industrial categories are mining, food, pulp and paper, textile, petrochemicals and pharmaceuticals. All of the mentioned industries produce wastewaters that have adverse impacts on each components of the environment such as water bodies, soil, air, human and the ecosystem [63]. Therefore, having a reliable wastewater treatment technology is important as it helps in reducing harmful impacts associated with industrial wastewaters. Due to economic and technical limitations of conventional wastewater treatment methodologies, many industries turn to membrane technologies to perform more reliable wastewater treatment operations. Among the various membrane materials, ceramic membranes have been gaining attentions for industrial wastewaters treatment because of their robustness and lower operational costs compared to polymeric membranes. However, despite the advances achieved in this technology, the potential of ceramic membranes for industrial wastewater treatment has not yet been fully realised. Ceramic membrane systems still require improvement in terms of investment cost, packing densities, selectivity and antifouling properties to satisfy future harsh operating conditions. It is crucial to review the investigations of the application of this technology to treat different industrial effluents to give a clear vision for the future [4]. It is therefore, the objective of this section to review some case studies and laboratory analysis of the application of ceramic membranes in some major industrial sections such as textile, pulp and paper, petrochemicals, mining, food, and pharmaceuticals to realize advantages , challenges, and prospects in ceramic membrane technology for industrial wastewaters filtration .

3.1. Pulp and Paper Industry

Pulp and paper industry depends heavily on a massive amount of water and its quality in the various stages of manufacturing processes. The manufacturing process mainly includes wood pulping and production of paper and generates wastewaters containing huge amount of pollutants depending upon the stage of the process. Generally, these pollutants are characterized by chemical oxygen demand (COD), biochemical oxygen demand (BOD), suspended solids (SS), level of toxicity, and colour [64]. The amount of pollutants discharge can also change significantly even at the same manufacturing process due to the use of various chemicals and seasonal variations. To protect human health and environment, many government agencies are forcing the paper industry around the world to treat wastewaters to comply with the environmental guidelines and standards before discharge. In addition, due to shortage of freshwater sources in some countries and increased legislation demands [65-67], the pulp and paper industry use advanced water treatment systems for effluent treatment and reuse it in manufacturing process. In the last two decades, membrane separation technologies have attracted more attention as an unconventional method for the treatment of the paper mill effluent. Successful demonstrations of membrane technology in treatment of wastewaters generated in paper manufacturing processes have been reported by researchers and paper manufacturing companies.

Ceramic membranes have been proposed for the treatment of pulp mill wastewater because of their remarkable chemical, thermal and mechanical stability under harsh operational conditions. Compared to polymeric MF, UF, and NF membranes [65-71], ceramic membranes can be cleaned with variety of harsh cleaning agents when fouling or scaling occurs , and solid performance over longer periods of operations can be guaranteed because of the nature of ceramics that have a combination of stronger bonds which is partially ionic and partially covalent [12, 72]. Several studies have been conducted to evaluate the performance of various ceramic membranes to treat pulp and paper industry wastewaters. Table 2 illustrates an overview of some investigations evaluating the application of ceramic membranes to treat effluents from pulp and paper mills. As shown in Table 2 , mainly α-$Al2O_3$ ceramic membranes with a selective separation layer of TiO_2 or ZrO_2 which are easily available in market with different pore sizes and MWCOs under various operational parameters have been applied in the experiments. Nataraj et al.(2007) developed a pilot plant which was a combination of α-Alumina tubular ceramic MF followed by Electrodialysis (ED) technology for the first time to treat real effluent samples from a paper mill with a COD concentration of 390 mg/L [73]. Their finding showed that ceramic MF plus ED hybrid process was capable to recover 80 percent of wastewater, while the remaining retentate could be used as a biomass. Their proposed plant was found to be more beneficial because the ceramic MF pretreatment could tolerate higher temperature of discharged wastewaters around 60 °C. Fouling during filtration was not severe and was reversible by membrane cleaning using hydrochloric acid and sodium bisulfate. Ebrahimi et al.(2015) employed two different multi-stage ceramic membrane process including hybrid Al_2O_3 MF followed by Al_2O_3/TiO_2 UF and Al_2O_3/TiO_2 UF followed by TiO_2 NF to treat alkaline bleaching effluent from sulfite pulp production with 10600 mg/L COD concentration [74]. Experiments were focused on investigating the suitability of ceramic tubular membrane systems as another possibility to conventional wastewaters treatment methods applied in paper mills. A comparison between two ceramic membrane processes showed that in terms of separation efficiency, the two-stage process employing MF plus UF was the best option for an efficient treatment of the bleaching effluent. More than 35 % of COD and 70% of remaining lignin level was reduced by applying the mentioned configuration. Also, approximately 186 and 140 L/m^{2}h of permeate flux were observed for ceramic MF and UF respectively. Membrane fouling is reduced significantly by applying ceramic MF prior to the UF stage. On the other hand, flux decline over time was observed during the UF/NF process. It was concluded that by applying hybrid ceramic MF/UF configuration, the volume of untreated bleaching effluent discharged from paper mills, would remarkably be reduced when applied to large-scale operations.

The other important application of ceramic membrane processes is recovering valuable materials from pulp and paper wastewaters. Researchers [75-84] employed various MF/UF/ NF ceramic membranes to treat and extract the lignin from black liquor generated in wood pulping process (Table 2). Black liquor is one of the waste streams in the paper production and is generally characterized by BOD, COD, dissolved inorganic compounds, lignin derivatives and bark particles. Lignin separated from black liquor during ceramic membrane filtration can be used as biofuel, dispersant, blinder, emulsifier and precursor for carbon fibres [75]. According to studies [75-85], by changing the MWCO of ceramic membranes, the molecular mass of lignin can be controlled during fractionation. Jönsson et al.(2008) employed hybrid ceramic UF membrane followed by polymeric NF membrane to compare lignin fractionation efficiency of the combined system with the direct polymeric NF [78]. Based on their results, a higher purity of lignin was achieved by applying ceramic UF pretreatment before polymeric NF stage. Furthermore, Žabková et al.(2007) used Al_2O_3-TiO_2 tubular UF ceramic membranes with 1,5, 15 KDa MWCOs to efficiently recover vanillin from lignin/vanillin mixture of various concentrations [86].

The application of ceramic MF membrane for the pretreatment of paper mill effluents prior to RO has been investigated by Pizzichini et al.(2005) [87]. The wastewater contains 1089 ppm of COD, 330ppm of SS and 435ppm total organic carbon (TOC). Their results showed that applying ZrO_2 ceramic MF with MWCO of 0.14 µ as a pretreatment step prior to RO can guarantee higher steady state flux rate around 150-200 L/m^2 h and less fouling indexes compared to all other polymeric MF and UF membranes investigated in their experiments. Integrating ceramic MF pretreatment followed by RO post treatment allowed the reuse of more than 80% of effluents as pure water, and it demonstrated the good potential to develop a large-scale industrial process appropriate for providing a large portion of water recovery, with an excellent chemical composition.

According to investigations mentioned in Table 2, there was no evidence of irreversible fouling observed when various cleaning methods such as washing and rinsing with tap water, permeate, deionized water, Alkaline and acid cleaning (NaOH and HCl solutions) were used for membrane cleaning. Approximately between 80-98 percent of pure water flux is restored by proposed cleaning method for MWCOs ranging from 1kDa to 20 KDa whereas for polymeric membranes , only up to 80% of pure water flux can be restored by a combination of rinsing and chemical cleaning [84, 88].

Based on the surveys presented in Table 2, applying ceramic MF/UF pretreatment can guarantee reasonable turbidity, COD, BOD and SS reduction in paper mill effluents. Using ceramic MF or UF pretreatment is beneficial in terms of obtaining stable operations and producing feed water of satisfactory quality for the NF and RO post treatments. Ceramic membranes are appropriate in dealing with aggressive and harsh environment due to high mechanical and chemical stability and higher durability compared to polymeric membranes. Recently, TAMI industries, one of the most prominent companies in the field of ceramic membrane manufacturing, introduced INSIDE CeRAM™ ranging from MF to fine UF with non-circular multi-channel tubular geometries and with membrane filtration area varying from 0.16-0.6 m^2 for the treatment of coating effluent in the paper industry [89]. However, the high capital cost and lower packing densities due to fragility of ceramics compared to polymeric membranes are the key challenges for many large-scale pulp and paper operations. Many pulp and paper plants around the world suffer from lack of space that may restrict the ceramic membrane unit installation. The capital cost of the ceramic membranes varies with the MWCO of the membrane. Typically, cost increases with the increase of membrane selectivity in terms of MWCO. Arkell and co-workers reported that the cost of TiO_2 NF ceramic membranes with 1KDa MWCO is about 2000 €/m^2 [75]. The cost decreased to 470 €/m^2 for Al_2O_3–TiO_2 Ceramic UF with 20kDa MWCO [75]. Moreover, the cost of UF ceramic membranes is about 33 times more than the polyamide RO membrane but their lifetime is longer. As an example , in one of the industrial installation of ceramic membranes unit in Japan, there was no report on the replacement of ceramic membrane unit after 16 years of successful operations [90]. Due to ongoing importance of ceramic membrane process for wastewater treatment purposes, the future researches may focus on developing wider range of cheaper inorganic membranes by introducing new fabrication technologies and new modules design to offer higher filtration capacities for employing in paper plants. Also, from technical and economical point of view, a feasibility study on the integration of ceramic membrane system with other physico-chemical treatment methods seems necessary [70].

Table 2: an overview of some investigations evaluating the application of ceramic membranes to treat effluents from pulp and paper mills.

Operational Parameters	Feed Source& parameters	Membrane characteristic	MWCO/Pore size	Flux	Rejection efficiency	Cost	Ref.
Pressure:1-5 bar Temp: 25°C Feed circulation velocities: 0.7, 1.3 and 1.8 m/s	First caustic extraction stage of a Kraft pulping Mill	Tubular Ceramic UF with an active layer of ZrO_2	MWCO of 10000 Da	35-87 kg/m^2h	Colour separation:59-74% TOC:49-53% TS:17%	-	[91]
Pressure:1-5 Bar Temp: 25°C Feed circulation velocities: 0.7, 1.3 and 1.8 m/s	First caustic extraction stage of a Kraft pulping mill	Tubular ceramic MF plus UF with an active layer of ZrO_2	MF: Avg. pore Dia of 0.14 µ UF: MWCO of 10KDa	53-78 kg/ m^2h	Colour separation:39-52% TOC:28-36% TS:10-14%	-	[91]
Pressure :4 bar Temp:25°C and 60 °C	Real effluent samples from West Coast paper mills, India Conductivity (mS/cm) :10.78 TDS (mg/L): 6046, Lignin (mg/L): 50 DOM (mg/L): 9.166, COD (mg/L):390 BOD (mg/L) :35	α-alumina Tubular Ceramic MF +ED	MF: 20 kDa MWCO and pore size of 1.5µm	113 L/ m^2h at 25°C 121 L/ m^2h at 60°C	Conductivity (mS/cm): 0.5 TDS (mg/L) :250, Lignin (mg/L) :5 DOM (mg/L) –, COD (mg/L) – BOD (mg/L) –	-	[73]
Transmembrane pressure(TMP):2-20 bar, Temp:90 °C CFV: 4–2 m/s	Untreated Kraft black liquor TDS (g/L) :183 ± 2.7 Total hemicelluloses (g /L) :3.56 ± 0.12, Total lignin (g/L): 63.8 ± 1.3	TiO_2 Ceramic NF	MWCO:1KDa	Avg.: 159 L/ m^2h	Retention of lignin and hemicelluloses :80 %	Membrane Price:1000€m^2	[75]
TMP :2 bar, Temp 90°C CFV of 5 m/s	Untreated Kraft black liquor TDS (g/L): 183 ± 2.7 Total hemicelluloses (g/L) :3.56 ± 0.12, Total lignin (g/L): 63.8 ± 1.3	Al_2O_3–TiO_2 Ceramic UF	MWCO:20K Da	-	TDS (g/L): 176 ± 6.3 Total hemicelluloses (g/L) :2.12 ± 0.06 Total lignin (g/L) 57.6 ± 2.4	Membrane Price: 470 €m^2	[75]
TMP:3,5, 7 Bar Temp:30±2°C	Untreated Kraft black liquor from wood pulping	α-alumina tubular ceramic UF/NF membranes with an inner layer of either TiO_2 or ZrO_2	MWCO: 1 KDa, 5KDa, 15 KDa	52 L/ m^2h for 15 KDa 12-25 L/ m^2h for 1KDa 30-75 L/ m^2h for 5KDa	Retention of organics between 60-70%	-	[76]
Pressure:0.1-0.6 MPa Temp: 25-80°C Flow speed: 1m/s	Untreated Kraft black liquor Feed Lignin concentration (g/L) : 48.8-78.6	ZrO_2 ceramic UF/NF	MWCO: 1 KDa, 5KDa, 15 KDa	TMP MWCO, and temp all affect the flux	Permeate lignin concentration(g/L) : 15.9-33.8	-	[77]
UF : TMP:100KPa,Temp: 90 °C CFV:5m/s NF: TMP:2.5MPa,Temp: 60 °C CFV:4m/s	Hardwood Black liquor TDS: 17 % wt. Ash(g/L):0.44 Lignin(g/L):59 , Hemicelluloses(g/L) :609	Hybrid Ceramic UF and polymeric NF	MWCO of UF: 15kDa MWCO of NF: 1 KDa	CFV, TMP temp all affect the flux	UF permeate: TDS:16 %, Ash(g/L):0.47, Lignin(g/L):54 Hemicelluloses(g/L):2.5 NF permeate: TDS:11%, Ash(g/L):0.61 Lignin(g/L):13, Hemicellulose(g/L):0.3	Production cost of €33 per tonne of lignin-UF and NF investment costs:(3300 and 2000 €/m^2) respectively	[78]
TMP:200kPa Temp:90°C	Black liquor TDS: 22% wt. Lignin(g/L):62 Ash content :43%	Al_2O_3-TiO_2 UF ceramic membrane	MWCO of UF: 15kDa	Avg. flux rate between 110-160 l/ m^2h	Approx. 35% lignin retention	Avg. 20 € per MWh of calorific value of the lignin fuel	[79]
Temp:150 °C	Kraft black liquor Lignin(g/L): 55.9-61.9	ceramic UF membrane	MWCO of UF: 5 and 15kDa	-	Approx. 70% lignin retention	-	[80]
MF: TMP:2-4 bars,Temp:120°C CFV:4 m/s UF: TMP: 2 bars,Temp:70-85°C CFV:5-8 m/s	Black Liquor Dry solids content:40.6-40.8% Total carbohydrate content : (g/kg DS):20-38 , lignin (g/kg DS):337-389	MF/UF ceramic Membranes	MWCO:300k Da-15kDa MF pore size:0.2 µm	-	Dry Solids content:27.6-37.9 % Total carbohydrate content(g/kgDS):9-23, lignin(g/kg DS):242-399	-	[82]

Table 2: Continued

For 5 KDa TMP:400 kPa,Temp:90°C CV:3.6 m/s For 15 KDa TMP:100k Pa, Temp:90°C CV:4.5m/s	Kraft black liquor Total dry substance(TDS):16 wt.% Lignin content (g/L) :56 Inorganics (g/L) :37	UF ceramic membrane	MWCO of UF: 5 and 15kDa	flux rate 451 L/ m^2h for 5kDa and 951 L/ m^2h for 15 kDa	66% lignin recovery for 5 KDa and 28% for 15 kDa	-	[81]
TMP:155 kPa pH:8.5-12.5	Lignin/Vanillin mixture lignin/vanillin mixture with different concentrations (g/L): 60/6-60/5-5/0.5-20/2	Al $_2O_3$-TiO_2 Tubular UF ceramic membrane	MWCO of UF: 1,5 and 15kDa	14 L/ m^2h for 5kDa and 4 L/ m^2h for 1kDa for 60/6 mix	Best rejection of lignin observed by using 60/6 g/L lignin/vanillin mixture and by employing 1 KDa MWCO at pH :12.5	-	[86]
-	Black liquor TDS (Total dissolved solids):10.3 % Inorganics:77% Organics:23% Lignin:17%	TiO_2 Tubular UF ceramic membrane	MWCO of UF: 5,10 and 15kDa	-	Permeate parameters: TDS:6.71-9.48 % Inorganics:82.6-92% Organics:8.05-17.4% Lignin:16.9-81.5%	-	[83]
TMP:200kPa Temp:32±2 ,63±3°C CFV:1.2 m/s	Black liquor TS(g/L):82-92 COD(g/L):75-89 Lignin(g/L):26	α- Al_2O_3 tubular ceramic MF membrane	Pore size:0.2µm-0.8µm	Avg. flux 200 and 400 L/ m^2h at Temp 32±2°C and 63±3°C respectively	Approx. 80 % of lignin retention achieved	-	[84]
TMP: 1 or 2 bar Temp:60 °C, CFV :4–5.6 m/s	Alkaline bleaching effluent COD(mg/L): 10,400 TOC(mg/L):4000 Na(mg/L): 2430	Hybrid Al_2O_3 MF and Al_2O_3/TiO_2 UF	MF: 0.1 µm, 0.14 µm, 0.2 µm UF: 5 kDa, 20 kDa, 0.05 µm	For MF and UF 186 and 140 L/ m^2h respectively	Using 0.1µm MF and 20-kDa UF COD removal 35%-45% Lignin removal:60-73%	-	[74]
TMP: 2 bar Temp:60 °C, a l CFV :0.3 m/s	Alkaline bleaching effluent COD(mg/): 10,400 TOC(mg/L):4000 Na (mg/L): 2430	Hybrid Al_2O_3/TiO_2 UF And TiO_2 NF	UF: 5 kDa, 20 kDa, 0.05 µm NF:1 KDa	UF Flux between 36.2 to 5.1 L/ m^2h after 6 hours	Using UF, 20 kDa and NF, 1 kDa COD removal 35%-40% Lignin removal:45-66%	-	[74]
MF: TMP:11 bar, Temp:30°C Feed flow: 4200 L/h	Raw Paper mill effluent SS (ppm):345,COD(ppm):1089 TOC(ppm): 435 Conductivity(µS/cm):2940	Tubular ZrO_2 Ceramic MF	MF MWCO:0.14 µm	150-200 L/m ^{2} h	MF permeate: SS (ppm):0 COD (ppm O2):891, TOC(ppm):361.4 Conductivity(µS/cm):2760	-	[87]

3.2. Textile Industry

The textile processing is one of the oldest and largest consumers of water. Textile production is complex and involves spinning, weaving, dyeing, printing, finishing and garments manufacturing. In almost all these stages of textile processing, wastewater is generated. The characteristics of these wastewaters depends on the type of process but in general it produces wastewaters of great chemical complexity and diversity including many dyes and chemicals containing trace and heavy metals such as Cr, As, Cu and Zn, non-biodegradable highly persistent organics and pesticides. Therefore, due to existence of persistent organics and poor biodegradability, advanced treatment processes are required, especially when the goal is reusing the treated wastewater [92-94]. For this reason, membrane technology can be considered as an efficient candidate for providing high quality permeates.

Many investigations have been conducted to study the application of different polymeric membranes either alone [95-104] or in combination with other techniques such as electrocoagulation [105] or biological treatment in the form of membrane bioreactor (MBR) [106-111] for the treatment of textile wastewaters, and for the recovery of dyes and salts [112-116]. However, in recent decades, ceramic membrane separation has attracted significant interest to treat textile effluents because of their reliable performance even in rough operational conditions [103, 117-126]. Table 3 illustrates an overview of some studies evaluating the performance of ceramic membranes to treat textile wastewaters .From technical point of view, reasonable reduction of BOD, COD, TDS, turbidity, SS, and moderate to high rejection of dye was achieved by applying $Al_2O_3/TiO_2/ZrO_2$ ceramic membranes with MWCOs ranging from 1KDa to 500KDa. Generally, low operating pressure was observed during experiments, while rejection rate and permeate flux could be modified by choosing the right cross flow velocity (CFV) and MWCO and operational conditions. Different methods including washing with tap, deionized, permeate, and alkaline and acid solutions were used for membrane cleaning. Around 90% flux recoveries was achieved after employing the cleaning protocols. As shown in Table 3, Alventosa-deLara et al. (2012) investigated the effectiveness of commercial multi-channel tubular ZrO_2-TiO_2 ceramic UF membranes in the removal of dye from the synthetic coloured feed solution. Based on their findings, at optimal operating conditions (CFV: 2.53 m/s and TMP: 4 bar) a significant dye rejection of about 95% was achieved [117]. In a similar study, Zuriaga-Agustí et al.(2014) achieved about 93% and 98.5% removal of dye and of organic matters respectively by applying tubular ZrO_2-TiO_2 ceramic UF membranes regardless of operational conditions [121]. Jedidi et al. (2011) employed ceramic MF membrane fabricated from mineral coal fly ash with average pore size of 4.5 μm to treat textile dyeing effluent with 3440 mg/L COD concentration. Approximately 74.5% and 99% of COD and turbidity reduction are achieved by using their proposed process [123]. Bhattacharya et al.(2010) used untreated sulphur black wastewater with 3910 mg/L COD concentration as a feed solution to study the efficiency of tubular multi-channel α-alumina and clay ceramic MF for dye and COD removal. 99% and 80% of dye and COD removal was achieved respectively [124]. Zebić Avdičević et al. (2017) achieved 98% of dye rejection by applying ZrO_2 ceramic UF with MWCO of 1 KDa [120] whereas only 62-79% of dye removal was achieved by applying TiO_2-ZrO_2 UF ceramic membrane with MWCOs ranging from 30 to 150 KDa [119]. The application of tubular ZrO_2 ceramic UF membrane for the pretreatment of biologically treated textile effluent prior to NF was investigated by Fersi and Dhahbi (2008) [103]. The effluent contains 329.4 mg/L of COD and 4240 mg/L of TDS (Table 3). Although the polymeric NF obtained more than 90% removal of colour and turbidity, adding ceramic UF pretreatment resulted in steady-state operation with longer constant and stable flux compared to direct polymeric NF membrane.

Ceramic membranes have been also applied for the fractionation of the salt-dye mixtures for resource recovery from the textile effluents. Ma et al. (2017) used multi-channel tubular tight UF ceramic membrane with TiO_2/ZrO_2 skin layer and porous Al_2O_3 support with MWCO of 8.8 KDa and pore size of 1.16 nm to treat synthetic negative-charged dye solution with NaCl and Na_2SO_4. Based on their results, ceramic membrane was efficient to purify high salinity dyeing effluent for salts and dyes recovery with more than 98% rejection of dye and less than 10% and 30% rejection of NaCl and Na_2SO_4 was achieved respectively [118]. Lima et al. employed ceramic membranes with average pore size of 0.14µm and 0.6µm to treat simulated textile wastewater sample prepared by deionized water and 0.25g/L indigo powder. About 100% percent of Indigo dye retention was observed in their experiments [122].

As an industrial example, in 2004, Societe d'Impression d'Hem(SIH), one of the major textile companies in France, installed Pall Membralox®ceramic ultrafiltration unit with a total filtration area of 432 m^2 in combination with biological treatment to treat its effluent with 10000-15000 mg/L COD concentration. The new installation was capable to recycle about 50% of the treated effluent for use as washing water for the printing machines which led to significant reduction in city water consumption consequently, remarkable reduction in operational cost [127].

As mentioned before, due to existence of persistent organic pollutants (POPs) in textile effluents which are highly persistent in terms of biodegradability, and also with large variation in produced wastewater composition in different stages, treatment of textile effluent is a complex process and advanced techniques are necessary [93]. Technically, employing ceramic MF and UF as the pretreatment steps before NF and RO is the best option to textile wastewaters, which contains high concentrations of COD/BOD and TDS. Ceramic membrane pretreatment was found reducing the upstream membrane replacement frequency because of their superior chemical stability and resistance to harsh cleaning agents. However, high investment cost limits their application in large-scale textile plants. In perspective of dyes and salt recovery, using tight ceramic UF membranes seems to be a better option in comparison with dense polymeric NF for the rejection of divalent salts such as Na_2SO_4. In summary, more focus need to be devoted in the development of cost-effective ceramic membranes with appropriate permeability and high filtration capacity for large scale textile operations. In fact, future research should focus on lowering the capital cost of ceramic membranes to make it more competitive to polymeric membranes. Life cycle cost assessments that includes Investment cost versus long-term operating cost of ceramic membranes is necessary to determine if installing such a large-scale ceramic membrane in potential textile plants can be a viable and profitable proposition. Coupling ceramics membranes with polymeric NF/RO membrane for the treatment of wastewaters with high organic and inorganic should be considered with design optimization to reduce the capital and operating costs.

Table 3: an overview of some investigations evaluating the application of ceramic membranes to treat effluents from textile industry

Operational Parameters	Feed Source& parameters	Membrane characteristic	MWCO/Pore size	Flux	Rejection efficiency	Cost	Ref.
TMP:4 bar Temp: 25°C CFV:2.53 m/s	Synthetic coloured solution with 50 mg/L dye concentration Conductivity (µS/cm):44.35	Multi-channel tubular ZrO_2–TiO_2 Ceramic UF	MWCO of 150 kDa	255.86 L/m²h	Significant dye rejection around 95%	-	[117]
TMP:3-13 bar	Biologically treated textile effluent from an activated sludge plant Conductivity (µS/cm) :8620 COD (mg/L) :329.4 TDS (mg/L): 4240	Tubular ZrO_2 ceramic UF followed by flatsheet polyamide NF	UF Pore size:50 nm NF pore size:2nm	At 11 bar TMP and VRF between 1-2.77:40-45 L/m ²h	Adding ceramic UF pretreatment before polymeric NF process guaranteed steady state operation with longer constant and stable flux compared to direct NF	-	[103]
TMP:1-3 bar Temp:25°C CFV: 3 m/s	Synthetic negative-charged dye solution with both inorganic salts $NaCl/Na_2SO_4$	Multichannel tubular tight UF ceramic membrane with TiO_2/ZrO_2 skin layer and porous Al_2O_3 support	MWCO:8800 Da Pore size:1.16nm	15-70 L/m ²h For TMP between 1 to 3 bar	Rejection of dye molecules: >98 % Rejection of NaCl<10% Rejection of Na_2SO_4<30% Efficient to desalinate high salinity dyeing effluent and recover salts and dyes	-	[118]
TMP:2-20 bar, Temp:30°C CFV: 3,4,5 m/s	Actual samples from a textile factory Conductivity (µS/cm) :2450-7780 COD (mg/L) :960-2525 Turbidity (NTU):35.84-83.34	Multichannel tubular TiO_2-ZrO_2 UF ceramic membrane	MWCO:30,50,150 KDa	90-160 L/m²h depending on CFV and MWCOs	Rejection efficiency (%) COD:62-79 Color:62-79 Turbidity > 99 For all MWCOs with the lowest CFV, higher removal of conductivity and COD achieved.	-	[119]
Temp:20±1 °C and 50±1°C CFV:1,2,3 m/s	Raw mercerization wastewater Conductivity (µS/cm) :75100 TOC (mg/L) :499.20 Turbidity (NTU):14.60 TDS(mg/L):20957 TSS(mg/L):100	Tubular multichannel ceramic UF 500KDa: with Al_2O_3, TiO_2,ZrO_2 active layer 2KDa: ZrO_2 active layer, Al2O3 support layer 1KDa:ZrO_2 active layer	MWCO: 500, 2 and 1 kDa	Raw effluent flux with 1 KDa membrane: 29.01 L/m ²h at the beginning 28.67 L/m ²h at the end	Best rejection efficiency achieved by 1KDa MWCO at CFV:3m/s ant Temp:20°C SS:92% Turbidity:98% Color:98% TOC:53%	-	[120]
Temp:25±1 °C CFV: 3 m/s TMP:1,2,3 bar	Simulated textile wastewater sample with various CMC concentrations	Tubular multichannel TiO_2-ZrO_2 ceramic UF	MWCO: 150 and 50 kDa	88.57-289.96 L/m ²h depends on MWCOs and CMC concentrations	Removal efficiency regardless of operational conditions: Organic matter:98.5% Dye:93%	-	[121]
Pressure :3 bar	Simulated textile wastewater sample prepared by deionized water and 0.25g/l indigo powder Turbidity ≥1000	Ceramic membranes	Avg.pore size diameter of 0.14µm and 0.60µm		Permeate Indigo concentration: 0 Turbidity:2-4	-	[122]
Pressure :1 bar	Textile dyeing effluent Conductivity (µS/cm) :6.16 Turbidity (NTU):45.5 COD (mg/L) :3440	ceramic MF membrane made of mineral coal fly ash	Avg.pore size diameter of 4.5 µm	100 L/m²h	Permeate quality: Conductivity (µS/cm) :5.38 Turbidity (NTU):0.58 COD (mg/L) :880	-	[123]
TMP:0.4-1.2kg/cm²	Untreated sulphur black wastewater Conductivity (µS/cm) :36.9 Turbidity (NTU):5912 COD (mg/L) :3910 TSS(mg/L):5550 TDS(mg/L):20200 Dye concentration(mg/L):890	Tubular multichannel α-Alumina and clay ceramic MF	Apparent porosity 36%		Dye removal :99%, COD reduction:80%	-	[124]

3.3. Petrochemical Industry

Petrochemicals are chemical products obtained from gas and petroleum processes. They generate a large volume of wastewater comprising of organic and inorganic materials with different compositions including oil compounds, dissolved formation minerals, production solids and production chemical compounds [128]. Effluents from petrochemical industry is one of the major polluter of aquatic life, and to comply with existing environmental policies and guidelines around the world, these wastewaters that contain a wide range of contaminants must be treated properly before discharging to the environment. Besides, the demand to reuse treated water has led petroleum industry to look for advanced efficient methods for treating petrochemical effluents [129].

Several research studies have been carried out to evaluate the performance of ceramic membranes in treatment of petrochemical effluents. Table 4 illustrates an overview of some studies assessing the efficiency of ceramic membranes to treat oily wastewaters. Madaeni et al. (2012) applied γ-Al_2O_3 ceramic MF with nominal pore size of 0.2 µm to treat coke-contaminated effluent derived from a petrochemical plant with 2210 mg/L COD concentration. At 15 bar pressure and 70 °C temperature, 100% of coke removal and around 72% of COD reduction was achieved [130]. Based on the good laboratory results achieved by the abovementioned study, Salehi et al.(2014) conducted some cost analysis to evaluate economic feasibility of applying 19 channel γ-Al_2O_3 ceramic MF with 91 capacity housing unit as a pretreatment method of coke-contaminated wastewaters. The designed unit was almost 100% efficient in coke removal under operating condition of 70 °C temperature and 15 bar pressure. A total capital investment of 535300USD was estimated by the study, and break-even point (BEP) and payback period (PBP) were near 3% and 2 years respectively. This results confirmed the γ-Al_2O_3 ceramic MF unit applicability as an economic potential pretreatment method for the removal of coke from petrochemical wastewaters [131]. In another feasibility study, Ghidossi et el.(2009) employed an on board continuous industrial scale treatment system composed of 19 channel ZrO_2–TiO_2 ceramic UF membrane with MWCO 300kDa in treatment of oily wastewater originating from passenger ships. From a technical point of view, a permeate flux of more than 100 L/m^2 h with 97% hydrocarbon removal was achieved by the proposed system. From the economic point of view, a satisfactory result was obtained where the cost of treated effluent by the proposed system was 250000€ per year for each passenger ship. In addition, the amount of wastewaters that are to be treated onshore was remarkably reduced by a factor of six. Also, the investment cost which was about 70000€ per ship, covered in a short period of time [132]. Abadi et al.(2011) employed tubular α-Al_2O_3 ceramic MF with a minimum pore size of 0.2 µm to treat oily wastewater samples taken from a refinery plant with 26 mg/L oil and grease content. Based on the experimental results, permeate quality met the national discharge standards in Iran after treatment with the proposed system where 85%, 100%, and 98.6 % reduction of oil and grease content, total suspended solids (TSS) and turbidity were achieved respectively [133]. Yang et al. (b) (2011), used synthetic oil in water emulsion mixed with powdered activated carbon (PAC) as a feed solution to study the removal efficiency and fouling behaviour of ceramic α-Al_2O_3 MF in the presence of PAC. The study showed that applying PAC had no effect on the removal of TOC with about 96% of TOC removal was achieved by using oily emulsion either alone or dosed with PAC. However, using PAC was an effective way to improve the permeation flux and reduce fouling as it provides mechanical scouring effect [134]. In another investigation, Yang et al (a) (2011), applied kaolin/MnO_2 bi-layer composite on ceramic Al_2O_3 MF to form dynamic membranes, and to enhance the separation performance in treatment of oily wastewaters. Based on the experimental results, the proposed dynamic membranes achieved the best oil separation performance under various operational parameters, and high permeate flux and oil retention ratio of 99% was observed. However, the fabricated dynamic membranes were only effective in neutral or alkaline conditions due to vulnerability of MnO_2 particles in acidic conditions [135]. Mullite and mullite –alumina ceramic MF manufactured from cheap kaolin clay and α-alumina powder with average pore size of 0.289 µm is used by Abbasi et al. (2010), to treat synthetic oily wastewaters with 510 mg/ L COD concentration. As shown in Table 3, at the best operating conditions (pressure: 3bar, CFV: 1.5m/s and Temp: 35°C) mullite–alumina ceramic membrane with 50% alumina content was the most suitable option where 90 % removal efficiency with moderate 104L/m^{2}h permeate flux was obtained. [136]. In another similar study, Nandi et al. (2010) evaluated the performance of MF ceramic membranes fabricated from various cheap inorganics such as quartz, feldspar, kaolin, boric acid, sodium carbonate and sodium metasilicate to treat synthetic oil-in-water emulsions. By applying this self-made membrane, oil removal of 98.8% was achieved [137].

Despite the advantages of membrane technology over conventional treatment techniques, there are some problems associated with membrane filtration of effluents generated during petrochemical operations. One of them is oil droplets accumulation on the membrane surface, which leads to formation of a concentration polarization layer, which consequently results in permeation flux reduction. Another major challenge is membrane fouling due to complex fouling characteristics of petrochemical effluents [128]. Over the past decades, many investigations have been conducted to reduce membrane fouling and enhance permeation flux. Surface modification [138, 139], enhancing shear stress at the membrane surface by applying pulsed flow [140, 141], turbulence promoters [142, 143], vibrating membranes [144, 145] and ultrasound cleaning [146] are some techniques that have been used by researchers to achieve better removal efficiencies and reducing fouling and concentration polarization. However, compared to the efficiency of polymeric membranes either alone or as a part of MBR systems [147-151], ceramic membranes offer better stability in petrochemical industry operational conditions. They can be cleaned more easily and greater longevity. Polymeric membranes can be easily degraded and fouled during treatment of petrochemical wastewaters specially when waxes and asphaltenes are present, and may require regular replacement [12]. According to Table 4, ceramic MF and UF has been successfully applied for the removal of coke from coke-contaminated petrochemical wastewaters. Ceramic MF and UF gives permeate of high quality with above 95% of oil rejection efficiency. Moreover, ceramic MF/UF has been applied to treat one of the most complex oily wastewaters called flowback and produced water generated from oil and gas drilling and hydraulic fracturing operations [152, 153]. Ceramic MF/UF is a reliable technology for the treatment of produced water compared to polymeric membranes because of the complex foulant profile of produced water compared to other types of natural or synthetic oily effluents. Produced water contains various type of dissolved minerals and salts [154]. Veolia Water technologies employed CeraMem® ceramic membranes at 60 locations to treat flowback and produced water and reuse them in the shale oil operations as fracking water, reducing mains water demand [155, 156]. However, according to Ji (2015), there are only over 75 commercial ceramic units worldwide for oily effluent treatment compared to more than 3000 polymeric MF/UF installations [128]. These limited number of ceramic membrane units proves that scaling up results from bench scale to large scale applications is due to high capital cost of ceramic membranes specially for large effluent volumes. Future studies should focus on developing precise predictive models that will allow investigating the applicability of experimental results in real large industrial operations. The main objectives of future investigations in this area should focus on improving packing densities, fabrication and coating techniques, antifouling properties, water permeability and oil separation efficiency of ceramic membranes as well as cost effectiveness [128].

Table 4: an overview of some investigations evaluating the application of ceramic membranes to treat effluents from petrochemical industry

Operational Parameters	Feed Source& parameters	Membrane characteristic	MWCO/Pore size	Flux	Rejection efficiency	Cost	Ref.
Pressure:15 bar Temp: 20-80°C CFV: 2m/s	Coke- contaminated Samples from a petrochemical company Turbidity (NTU) :251 TDS (mg/L): 265 TSS (mg/L):27, COD (mg/L):2210 BOD (mg/L) :225 VOC in 550 °C (mg/L):17	Γ- Al_2O_3 based ceramic MF	Nominal pore size of 0.2 µm	The flux was increased by increasing feed temp. 80% of flux recovery observed by proposed cleaning by NaOH	Turbidity (NTU) :13 TDS (mg/L): 32 TSS (mg/L):11 COD (mg/L):640 BOD (mg/L):55 VOC in 550 °C (mg/L):12	-	[130]
Pressure:15 Bar Temp: 80°C	Coke-contaminated effluent from a petrochemical company Turbidity (NTU) :251 TDS (mg/L): 265 TSS (mg/L):27, COD (mg/L):2210 BOD (mg/L) :225 VOC in 550 °C (mg/L):17 Coke content (wt.%): 0.1	19 channel γ-Al_2O_3 based ceramic MF with 91-capacity housing	Channel diameter 4mm	Min. permeated water flux:500L/m^{2}h	Almost 100 percent efficient in coke removal	Economic Evaluation based on 19-channel membrane for large scale application Total capital investment :535300 USD BEP: 3% PBP:2 years	[131]
TMP :1.25 bar Temp:32.5°C and 60 °C CFV:2.25 m/s	Samples derived from a refinery plant Turbidity (mg/l) :21 TOC (mg/L): 141 TSS (mg/L):92 Oil and grease content (mg/L):26	Tubular α-Al_2O_3 ceramic MF	Min. pore size of 0.2 µm	Water flux: 500L/m^{2}h	Turbidity (mg/l) :0.3 TOC (mg/L): 7 TSS (mg/L): Trace Oil and grease content (mg/L):4	-	[133]
TMP:2.6-3.3 Temp:20 °C	Oily wastewater samples from passenger ships Turbidity (NTU) :150-250 Dry matter (g/L): 12-14 Conductivity (mS/cm):17-20 Hydrocarbon (ppm):35	ZrO_2–TiO_2 ceramic UF membrane	MWCOs: 0.1µm and 300 kDa	Permeate flux: 100 L /m^2 h	MWCO 0.1 µm: Turbidity (NTU) :60 Dry matter (g/L): 9.8 Conductivity (mS/cm):17.1 HC(ppm) <1 MWCO 300 KDa: Turbidity (NTU) :59 Dry matter (g/L): 7.3 Conductivity (mS/cm):18.7 Hydrocarbon (ppm) <1	Scale up 19 channel membranes with MWCO 300-kDa composed of 19 channels was economically attractive 250,000€ per year was the cost of treated effluent by the proposed system	[132]
Pressure 3 bar Temp 35 °C CFV :1.5 m/s	Synthetic oily wastewater TSS(mg/L):60, TDS(g/L):25 COD(mg/L):510, TOC(mg/L):1000 Turbidity(NTU):89	Mullite and mullite alumina MF with 50% and 75% of alumina	Avg. pore size: 0.289 µm	Permeate fluxes Mullite :72 L /m^{2}h Mullite –alumina (50%):104L/m^{2}h Mullite –alumina (75%):244 L/m^{2}h	Removal efficiencies: Mullite ceramic MF: ~ 94% Mullite –alumina (50%): ~90% Mullite –alumina (75%): ~81%		[136]
TMP:0.69 bar Temp:25 °C	Synthetic oil-in-water emulsion Oil concentration(mg/L):250	ceramic membrane prepared from cheap inorganic substances	82.67 percent pores with diameter between 0.1 to 0.3 µm	19.3 L/m^{2}h	98.8% oil rejection efficiency	-	[137]
Pressure :1 bar Temp 35 °C CFV :4.5 m/s	Synthetic oil-in-water emulsion with powdered activated carbon P-xylene (mg/L):3000 TOC(mg/L):3817	Ceramic α-Al_2O_3-ZrO_2 MF	Nominal pore size: 0.2 µm	Pure water flux: 1344 L/m^{2}h Flux enhancement observed by dosing emulsion with powdered activated carbon because of scouring effect	96% TOC and P-xylene removal efficiency	-	[134]
TMP:1-2 bar Temp 10-40 °C CFV: 1 m/s	Synthetic oily wastewater	Ceramic Al2O3 MF coated with Kaolin/MnO_2	Nominal pore size: 1.0 µm	Permeate flux 120.1 L/m2h at 10°C 153.2 L/m^{2}h at 40°C	99.9% of oil retention at 10°C 98.2% of oil retention at 40 °C	-	[135]

3.4. Food Industry

The food industry consumes a massive amount of water. It is used as an ingredient of their products, in production processes, general cleaning, and sanitation and disinfection purposes. Depending on the operation processes and type of products, the volume and characteristics of these effluents can vary and sometimes difficult to predict. Generally, they are characterized by high BOD and COD plus oils, fats and nutrients. In addition, micropollutants including hormones, surfactants, antibiotics, and pesticides may be present. Consequently, effluents from food industries are a threat to the environment and appropriate treatment systems are required to remove undesirable components before discharge or reuse [157-159].

Ceramic membranes are important processes in food industry. They can be used for a variety of purposes such as treatment and clarification of effluents generated during dairy, juice, beverage, beer, wine, vinegar , sugar, olive, corn, soy sauce, meat, poultry and seafood production processes [160-176]. Ceramic MF and UF have received a lot of attention in the treatment of food industry wastewaters because of their long-term solid performance in these applications over the polymeric membranes [12]. Table 5 shows the results of some investigations evaluating the application of ceramic membranes to treat effluents from food industry. Several studies have been conducted to evaluate the efficiency of ceramic MF fabricated from natural clay and $Al_2O_3/ZrO_2/TiO_2$ materials in treatment of food industry effluents. Kumar et al.(2016) applied cheap ceramic MF membranes fabricated from clay materials with a pore size of 0.309 µm to treat raw diary waste water with a COD concentration of 1462 mg/L. Based on their results, the COD concentration in permeate was reduced to 135 mg/L which was below the acceptable limit of permeate stream (<200 mg/L) [160]. As compared to similar studies done for the treatment of dairy wastewater with polymeric membranes [177-179], good results were obtained in terms of COD removal, with 91% of COD reduction achieved by the use of this system, while for polymeric MF, UF and NF membranes the rejection rate was between 78% and 98%. However, low-pressure operation of around 2.07 bar with a steady state flux was observed during experiments using ceramic MF. On the other hand, testing with polymeric NF membranes, resulted to pressure reaching about 10 bar in some experiments. This suggests MF ceramic membranes option is more energy efficient than polymeric membrane which is a trade-off between the capital and operation costs. Hart et al. (1988) examined the possibility of employing bench-scale ceramic Al_2O_3 MF membrane for the treatment of poultry scalder and chiller waters for reuse purposes. Based on the experimental results, ceramic MF with 0.2-0.45 μm pore size was an appropriate treatment method, and the permeate quality met the standards to reuse where the permeate turbidity was less than 1NTU from the 0.2 μm filter. However, their study suggested that longer term operations using commercial scale equipment are necessary to achieve a reliable information and make a precise financial analysis [161]. Değermenci et al. (2016) applied α-Al_2O_3/ZrO_2 ceramic MF with 0.1 μm pore size in combination with biological system as a part of a jet loop MBR to evaluate the efficiency of this combined system for the treatment of high oxygen demanding olive mill effluent. The COD and initial phenol concentrations were between 55730-91550, and 2439-4509 (mg/L) respectively (Table 5). COD and a total phenol removal of 93% and 87% were achieved respectively. The removal efficiency remained almost stable by using combined ceramic MF and jet loop bioreactor even at various hydraulic retention times [162].

Li et al.(2010) and Almandoz et al.(2010) employed α-Al_2O_3& ZrO_2 ceramic MF with pore sizes ranging from 0.14 μm to 0.75 μm for the treatment and clarification of raw rice wine and corn syrup samples. Turbidity reduction between 91.2% to 99.6% and insoluble residues rejection of 63.9% to 99.8% were achieved depending upon membrane pore size which can be a reliable alternative over conventional technologies applied in the wine and corn syrup clarification [163, 164]. In a similar investigation conducted by Li et al. (2007), α-Al2O3 & ZrO2 ceramic MF ceramic with 0.2, 0.5, 0.8 μm of pore size has been used to remove bacteria from raw soy sauce sample. More than 99% of bacteria removal from raw soy sauce samples was achieved by 0.2μm ceramic Al_2O_3 MF membrane. On the other hand, the percentages of removing bacteria were 97.5% and 93.8% for 0.5μm and 0.8μm pore sizes respectively. The results emphasized the importance of selecting membrane with an appropriate pore size in the filtration process [165].

The efficiency of ceramic MF and UF for the treatment of effluents from the seafood processing section has also been studied. Kuca and Szaniawska (2009) used 23-channel $Al_2O_3/TiO_2/ZrO_2$ ceramic 150 kDa MF for the removal of protein from salted wastewater originated from fish processing operations. They reported 81% protein removal from the salted wastewater [166]. In another comparable study conducted by Afonso and Bórquez (2002) , mono-tubular ZrO_2-TiO_2 ceramic 15 kDa UF has been applied for the treatment of wastewater originated from a fish meal plant [167]. The flux rate was found to be about 4 times higher than that observed in Kuca and Szaniawska experiments (Table 5); however, a total protein rejection of only 26% was achieved. It seems that the number of channels, MWCO and type of ceramic materials affects the protein rejection. In general, multi-channel ceramic MF membrane has higher packing density which is preferred over mono-channel element. Diná Afonso et al. (2004) compared the efficiency of ZrO_2-TiO_2 mono-channel tubular ceramic 15 kDa UF with multi-channel tubular $Al_2O_3/TiO_2/ZrO_2$ Ceramic 1KDa NF in protein removal from a fish meal plant's wastewaters. An almost similar maximum protein rejection of 62% and 66% were observed using ceramic UF and ceramic NF respectively. However, permeate flux was approximately 1.3 times higher in the ceramic UF than ceramic NF. This led to an economic assessment for industrial scale up based on the use of ceramic UF membranes. Based on the financial analysis results (details in table 5), applying ceramic UF for the treatment of fish meal wastewaters was economically feasible for the purpose of proteins recovery [168]. Walha et al. (2011) used multi-channel TiO_2 ceramic MF with the pore size of 0.1 µm as a pretreatment step prior to polymeric NF stage to treat raw tuna cooking juices. Compared to direct polymeric NF of tuna cooking effluent, they succeeded to improve the permeation flux by nearly 3.3 times by applying ceramic MF technique. Although ceramic MF and UF membranes are not appropriate for the rejection of low MWCO matters, they can make an impact when combined with polymeric NF membranes. Such hybrid system is typical nowadays in food wastewater treatment facilities [169].

Resistance analysis and fouling behaviour for ceramic MF and UF in food industry wastewaters have been investigated by some researchers. The membrane fouling is an inevitable phenomena that occurs due to adsorption of proteins and accumulation of unwanted compounds on the membrane surface [160]. According to studies shown in Table 5, cake filtration and pore clocking are the two main mechanisms of fouling which is a normal phenomenon in MF and UF filtration processes [163-165]. Although severe fouling observed during the filtrations of some feed solutions by ceramic membranes, original flux almost completely recovered by cleaning processes utilizing sequential washing with chemical detergents and alkaline and acid solutions [161, 163, 167]. In addition, Kuca and Szaniawska (2009) realized that changes in pressure and pH in a laboratory scale have different effects on the fouling behaviour of ceramic membranes used for the treatment of salted effluents from fish processing operations. The effect of TMP ranging between 0.5 to 2 bar (Table 5) was negligible on membrane fouling; however, the lowest fouling observed at pH equals to 9 [166].

Ceramic membranes have been applied practically in various sections of food industry for treatment of effluents. As an example, Isoflux™ ceramic MF membranes made by TAMI industries have been successfully applied to more than 50 plants around the world for various purposes in dairy industry such as bacteria reduction in milk and cheese brine and miscellar casein separation from milk. Isoflux ™ membranes offer better selectivity efficiency and higher permeation flux over polymeric membranes whereas milk fractions could not successfully obtained due to large pore size distribution [180, 181]. Tetra Alcross® Bactocatch and Atech Innovations GmbH products are two other manufacturers of commercial ceramic membrane systems which successfully applied their products worldwide for the removal of bacteria and spores from milk , polishing filtration of citrus fruit juice, production of glucose from sorghum, clarifying beverages , and production of sugar syrup [182, 183].

As mentioned before, a specific problem associated with the filtration of food processing wastewater is the accumulation of unwanted compounds on the membrane surface that if improperly washed may become a source of harmful bacteria [184]. The application of ceramic membrane technology can guarantee food hygiene due to its ease of cleaning and sterilization [185]. Moreover, ceramic membranes were successfully applied for milk and other dairy productions fractionation. However, traditional polymeric membranes cannot achieve similar proper results due to wide pore size distribution which causes transmission of components that should be retained through the larger pores, and retention of components that should be passed by smaller pores. Despite the successful application of ceramic membranes in laboratory scale and some commercial systems, there is a major limitation to the industrial scale implementation of ceramic membranes in food industry due to their high capital cost. In addition, a better understanding of fouling mechanisms by analysing the interactions between various ceramic materials and the wide variety of foulants that exists in food processing effluents can result in more stable long-term operations and lower operational costs [12].

Table 5: an overview of some investigations evaluating the application of ceramic membranes to treat effluents from food industry

Operational Parameters	Feed Source& parameters	Membrane characteristic	MWCO/Pore size	Flux	Rejection efficiency	Cost	Ref.
Pressure:2.07-4.14 bar Temp: 25°C Cross flow rate: 5.55-22.2 m/s × 10^{-7}	Raw diary wastewater Conductivity (mS/cm): 853 Total suspended content (mg/L): 976 TSS (mg/L):254, TDS (mg/L):722 BOD (mg/L) :758, COD (mg/L):1462	Low cost tubular ceramic membrane fabricated from natural clay materials	pore size: 0.309 µm	Avg. permeate flux: 9.3 L/m²h	COD (mg/L):135 91 % of COD removal	Membrane Cost: 69 $/m²	[160]
Pressure :1 Bar Temp: 15-52°C	Poultry chiller and scalder water and frankfurter chiller brine Total solids (%): 0.14 -15.7 Ash (%): 0.048-14.07 Nitrogen (%) :0.009-0.025 Fat (%): 0.02-0.05	Al_2O_3 based ceramic MF	pore size: .02-.45 µm	Avg. permeate flux: 110-440 L/m²h	Total solids (%): 0.07-14.75 Ash (%): 0.04-13.96 Nitrogen (%) :0.003-0.025 Fat (%): 0.014-0.025 Turbidity (NTU):<50 –with manty less than 1	-	[161]
Pressure:0.8-2.8 bar Temp: 25°C Cross flow rate:20-65 L/min	Olive mill wastewater COD (mg/l) :55730-91550 BOD(mg/L):29930-38600 TOC (mg/L): 18620-23454 Conductivity (mS/cm): 10.04-12.01 Total phenol (mg/L):2439-4509	Jet loop MBR using α-Al_2O_3 –ZrO_2 Ceramic membranes with 37 channels	Pore size:0.1 µm	Avg. permeate flux:0.9 L/m²h for 0.418 m² of membrane surface area	COD removal:91-93% Total phenol removal:80-87%	-	[162]
TMP:1 bar Temp: 15±3°C CFV:1.10 m/s	Raw rice wine samples Total insoluble solids (g/L):12.7 Crude protein (g/L):10.8 Turbidity (NTU): 35.3	α-Al_2O_3 & ZrO_2 Ceramic MF	Pore size: 0.2-0.5 µm	18-33 L/m²h	Total insoluble solids (g/L):0.7-1.2 Crude protein (g/L):2.56-4.32 Turbidity (NTU): 2.12-3.10	-	[163]
TMP:0.5 bar Temp: 60°C CFV:0.5 m/s	Corn Syrup Turbidity (g/ L $BaSO_4$):1.343 Insoluble residues (%w/w):0.332 Total proteins:(%w/w):0.1	Composite tubular ceramic MF fabricated from alumina-silicate materials	Pore size: 0.5 ,0.75,0.14 µm	Permeate flux: 77.5-136.2 L/m²h	Turbidity reduction:97.4-99.6% Insoluble residues rejection:63.85-99.75% Total Protein Rejection:70-80%		[164]
TMP:1 bar Temp: 22±3°C CFV:0.58 m/s	Raw soy sauce Turbidity(NTU):18.7 Total solids(kg/L):0.38 TN (g/100mL):1.74 Total bacterial count 3200	α-Al_2O_3 & ZrO_2 Ceramic MF	Pore size: 0.2,0.5,0.8 µm	3.5-12 L/m² h Highest flux: 0.2 µm(α-Al_2O_3) Lowest flux: 0.8µm(α-Al_2O_3)	Raw soy sauce permeate Turbidity(NTU):0.813-1.61 Total solids(kg/L):0.26-0.31 TN (g/100mL):1.64-1.70 Total bacterial count 30-200 >99% bacteria removed from raw soy sauce	-	[165]
TMP:0.5 to 2 bar Temp:20°C CFV:4 m/s	Salted wastewater from fish industry BOD (mg O_2/dm³):2050-7980 COD(mg O_2/dm³):4250-14600 Protein (wt.%):0.1-2.5	23 channel Al_2O_3/TiO_2/ZrO_2 Ceramic MF	MWCO:150k Da	Flux:19.1-27 L/m²h	Protein Rejection:81% BOD:72% COD:60%	-	[166]
Pressure: 4 bar CFV:4 m/s Temp:20 °C	Effluents from a fish meal plant	ZrO_2- TiO_2 mono-tubular ceramic UF	MWCO:15 k Da	95.4 -97.7 L/m²h	Total proteins rejection:26% Oil and grease rejection:40% Total solids rejection:4.1% UF with lower MWCO or NF is recommended for efficient protein removal.	-	[167]
Pressure :3-4 bar Temp:21 °C CFV:3-4 m/s	Effluents from a fish meal plant Total Solids (g/l) :24 Volatile solids (g/l):18.9 Total proteins (g/l) 15.5 Oil and grease (g/l) 1.21	Mono-tubular ZrO2–TiO2 UF membranes	MWCO:15 KDa	30.1-38.9 L/m²h	Protein Rejection:49-62%	A plant handling 10 m3/h of effluent: NPV:160000 USD Interest rate of return :17% Payback time: 8 years	[168]

Table 5: Continued

Pressure :3-4 bar Temp:25 °C CFV:3-4 m/s	Effluents from a fish meal plant Total Solids (g/l) :24 Volatile solids (g/l):18.9 Total proteins (g/l) 15.5 Oil and grease (g/l) 1.21	19 channel tubular $Al_2O_3/TiO_2/ZrO_2$ Ceramic NF	MWCO:1 KDa	22.3-32 L/m^{2}h	Protein Rejection :63-66%		[168]
MF: Pressure:2 bar Temp:25 °C CFV:3.1 m/s NF: Pressure 35 bar Temp:40°C CFV:2.5 m/s	Raw tuna cooking juices Turbidity(NTU):496±7 SS(g/L):2.1±0.1 COD (g/L):23.5±0.7 Dry matter(g/L):147.7±3	Multi-channel TiO_2 ceramic MF followed by polymeric NF	MF Pore size :0.1µm	MF/NF :90-100 L/m^{2}h NF:30 L/m^{2}h	Retention of inorganic compounds:70-76 % Permetation flux significantly increased by applying ceramic MF pretreatment		[169]
TMP:1.75 Temp:50 °C	Rinsing water from bottle washing machine COD (mg/L):240-580	Al_2O_3 Ceramic MF	Pore size :0.2µm	40 -160 L/m^{2}h	Turbidity retention :99% COD rejection:30%		[170]

3.5. Pharmaceutical

Water is an inevitable component in pharmaceutical manufacturing operations, and it is widely used in different stages of processing, from formulation to production of drugs for use as medications. The wastewaters generated in different stages contain a wide variety of organic and inorganic compounds and impurities. In addition, removal of pharmaceutically active compounds (PhACs) and endocrine disrupting compounds (EDCs) from generated wastewater is essential and has become one of the major concerns in recent years. Improper and insufficient treatment of pharmaceutical effluents may cause PhACs return to human body through water cycle which can lead to irreversible consequences. EDCs are also known to disrupt the human endocrine system [186, 187]. It is estimated that many wastewater treatment systems are not designed to remove specific compounds, making them inefficient at removing pharmaceutical compounds before effluents are discharged to the environment. Therefore, the Pharmaceutical industry requires a robust and high quality wastewater treatment system to meet the discharge limits. [188].

The application of MF, UF and NF polymeric membranes either alone or as a part of MBR has been studied in pharmaceutical industry for various purposes. These include removing of organic compounds and endocrine disruptors from the pharmaceutical effluent, separating and recovering of antibiotics from the pharmaceutical wastewater, and isolation and purification of biologically active compounds such as viruses and enzymes [9, 189-199]. However, polymeric membranes are sensitive to aggressive cleaning agents, so they cannot be efficiently sterilized and should be replaced at more frequently.

The applicability of ceramic membranes is increasing in pharmaceutical industry due to its better capability in terms of repeated steam sterilization and ease of cleaning with harsh chemicals compared to polymeric membranes [8, 200]. Hydro Air Research Italia membrane systems are operating successfully for antibiotic recovery by using ceramic membrane in fermentation broth clarification step before multistage RO which ensures excellent protein removal and high permeate flux [201]. GlaxoSmithKline a British pharmaceutical company replaced polymeric membranes with Star-Step™ ceramic membrane system supplied by Mantec filtration. It consists of 4 banks of 8 housing with 108 ceramic membrane unit in each housing of 208 m^2 membrane area at its antibiotic drug processing plant. Several economic advantages such as less maintenance requirement, longer membrane life span, energy saving by using star-shaped flow channels and easier membrane cleaning were observed by replacing polymeric membranes with ceramic units that led to the reduction in operating costs. From the technical point of view, the ceramic unit represented remarkable filtration performance, doubling the flux of previous polymeric membrane system [202]. Inopor GmbH, one of the suppliers of ceramic membranes for the purpose of liquid filtration, applied ceramic UF in the treatment process for "water for injection" in pharmaceutical industry. Ceramic UF has to be installed to prevent the growth of microorganisms that would lead to contamination of piping system and the purified water after electrode ionisation stage in pharmaceutical industries [37]. Polymeric membranes are not appropriate for this purpose due to low resistant against organism and disinfection by steam. Inopor® ceramic membrane showed excellent efficiency for this requirement [37].

In summary, application of ceramic membranes in pharmaceutical section have the benefits of being frequently bio inert, persistent against bacteria and can withstand repeated chemical and steam sterilization at high temperatures which polymer membranes may fail to tolerate [6, 200]. Employing ceramic UF as a part of hybrid system for generating ultrapure "water for injection" for medical liquids including heat exchange, reverse osmosis, membrane degasification and electrode ionisation can appropriately prevent the growth of microorganisms and pollution of piping system where the application of polymeric membranes is not possible due to poor resistance against periodic steam sterilization. However, very selective concentrations and recovery of vitamins, enzymes and antibiotics is another subject of interest in pharmaceutical industry and most of the ceramic membranes show poor selectivity properties. Future research in this industry sector may focus on introducing new polymer-ceramic composite membranes which can guarantee high selectivity and great tolerance to aggressive conditions. Introducing new polymers with high selectivity for the purpose of coating on ceramic nanofilters with lower MWCOs below 450Da maybe an efficient way for complete separation of pharmaceutics with complex structures out of wastewater [8, 37].

3.6. Mining Industry

Acid mine drainage (AMD) is the most common water pollution issue in the mining industry. It is produced when rock containing sulfur-bearing minerals is exposed to oxygen and water. Typically, AMD is characterized by low pH, high specific conductivity and high concentrations of heavy metals and other toxic elements [203-205]. If AMD is left untreated and gets to nearby water systems such as rivers, streams or lakes, it can contaminate surface and groundwater and may disturb the reproduction system of aquatic life. It also affects metal and concrete structures by corrosion, and can raise water treatment costs. Consequently, the development of cost-effective and efficient treatment solutions for the AMD problem has been the subject of many researches during recent years.

Some investigations have been published on wastewater treatment and recovery of heavy metals from the mining effluents by various pressure-driven polymeric UF/NF and RO systems [206-219] , and has shown that polymeric NF and RO have quite similar efficiency in the removal of heavy metals from mining effluent. However, applying polymeric NF due to higher flux, acceptable rejection efficiency and, lower energy consumption was more appropriate than RO at comparatively low-temperatures. On the other hand, using RO is preferable over polymeric NF at high temperature conditions [208, 217, 219]. Membrane fouling, however, is the major challenge for using polymeric membrane in harsh environment such as mining wastewater treatment. In contrast, ceramic membranes may be an appropriate alternative over polymeric membranes due to their significant chemical, mechanical and thermal stability under harsh operating condition like what is expected in actual mining operations. As an example, Blackhawk Colorado AMD treatment facility replaced tubular polymeric membranes with ceramic membranes in 1995, and were still in service till 2013 which proved the durability of ceramic membranes compared to polymeric membranes lifespan ranging between 6 to 9 months [220]. Another successful example of commercial application of ceramic MF system is the new wastewater treatment plant installed in 2009 at the Upper Blackfoot Mining Complex located in Montana, USA. Compared to high density sludge clarifier system installed at this facility, ceramic MF could operate at very acidic condition which is an advantage for AMD treatment. Lower pressure operations, smaller footprints, lower chemical consumption, labour and power costs were some significant improvements achieved by replacing the clarifier system by ceramic MF[220, 221]. Liqtech International Inc. installed fifteen particle removal and six dewatering systems using CoMem® SiC ceramic membrane with 25 and 146 mm outer diameter (OD) in one of the largest mining operations in Europe. Particle removal system was placed in a 99X glassfiber reinforced plastics multihousing in racks of 6 housings, and the dewatering system was placed in a single polypropylene housing in racks of 6 housing. The actual membrane capacity was 960 m3/h and the proposed system could remove heavy metals as required and stable permeability and steady state permeation flux were observed during operations. However, there is no information available in supplier website regarding cost analysis [222]. In addition, based on Mine Waste Technology program 2002 annual report, Stewart compared investment and operating cost of 1136 L/min polymeric and ceramic membrane systems. The capital cost of 1136 L/min ceramic membrane system was about 1900000 USD while for the polymeric membrane system with the same capacity, the capital cost was about 1800000 USD which was only about 5% cheaper compared to ceramic membrane system. On the other hand , the annual operating cost of 1136 L/ min ceramic membrane system was about 55 % less than the similar capacity polymeric membrane system due to lower maintenance cost of ceramic membranes which is a big difference (about 260000 and 470000 USD/year for ceramic and polymeric units respectively) [220].

A review of previous commercial scale application of ceramic membranes in treatment of harsh mining effluents proves that ceramic membranes afford specific advantages in this application like long-term durability, ease of cleaning, better chemical and mechanical stability and lower annual operational cost compared to polymeric membranes. However, the main disadvantages of ceramic membranes are high fabrication costs of ceramic components and high capital cost associated with installation of commercial scale ceramic membrane units in mine sites [6]. Future development should be based on new ceramic components with reasonable fabrication cost and appropriate permeability which can handle stable and steady state operations even under harsh conditions faced in mining operations and more space-effective ceramic membrane modules with smaller footprints [8, 12]. The main problems associated with the treatment of AMD are managing the large amount of sludge, which arises during treatment process, and various chemical processes with complicated behaviour and various reaction rates in AMD. A design an appropriate hybrid system by combining ceramic MF/UF and other chemical and mechanical techniques such as electrocoagulation and high shear reactors for reducing treatment sludge rates of chemical reactions in AMD should be considered in future researches [220, 223, 224].

4. Ceramic Membrane Reactors for Advanced Oxidation Processes (AOPs)

AOPs are a group of chemical oxidation processes designed to remove natural organic compounds (NOM) and decompose of persistent non biodegradable organics in wastewater through reactions with hydroxyl radicals (OH). OH generation is possible through different techniques including ozone, H_2O_2, ultraviolet (UV), Fenton reaction, electrolysis and photocatalysis [225].

Although membrane filtration is an effective technique for removal of wide range of toxic elements from the wastewaters, it has limited ability to remove some dissolved organics, especially in the range of MF/UF. Therefore, combined membrane separation with AOP in a reactor as a single system looks like an appropriate solution to provide flexibility and improve the limitations of both AOPs and membranes [225, 226]. However, one of the major drawbacks associated with advanced oxidative membrane reactors is conflict of hydroxyl radicals and membrane polymers [225]. Consequently, researchers have tried to develop various ceramic membrane reactors for AOPs to overcome the Incompatibility issue between hydroxyl radicals and membrane polymers. In addition, ceramic membranes are more resistive to UV radiation whereas polymers may deteriorate easily [226-228].

Ozonation, which refers to the application of ozone in wastewater treatment, is one of the advanced oxidation processes involving the production of very reactive oxygen species that are able to attack and degrade a wide range of organic pollutants in the wastewaters [226, 229]. This method has been successfully combined with ceramic membrane filtration process for more effective treatment of industrial complex wastewaters and efficient removal of organic toxics. Majority of investigations has been applied ozonation either as pre-treatment stage for removal of toxic organics prior to the membrane filtration step [230, 231]or post-treatment stage to treat both permeate and retentate [232-237]. However, studies about advanced ozone ceramic membrane reactor as an integrated process is limited in literature. A few works successfully demonstrated the use of inorganic membranes and ozonation in a hybrid reactor to achieve higher TOC removal with minimum amount of ozone usage [238-240]. Further work is required to address the high energy consumption and toxicity issue associated with ozone generation [229] to make this method an economic and reliable alternative for removal of organic pollutants from industrial effluents in large-scale operations. Figure 4 illustrates an ozone membrane reactor. Numbers 1 and 2 on the Figure Indicate alumina capillary membrane and zeolite membrane unit respectively.

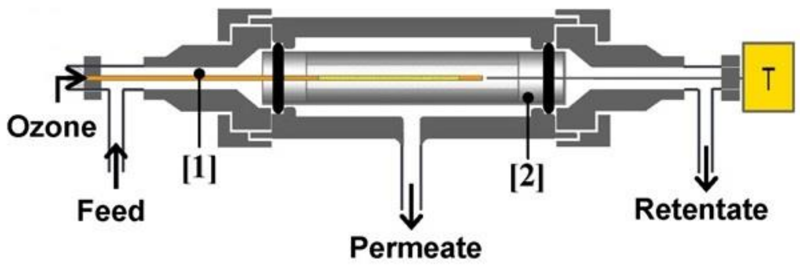

Fig 4. Ozone membrane reactor (reproduced from [241] with permission from the Journal of Membrane Science)

Researchers widely studied reactor configuration that is called photocatalytic ceramic membrane reactors (PMRs). It consists of a ceramic membrane module as a second stage and photocatalytic reactor as an OH generator in an integrated hybrid process. Successful laboratory-scale applications of this method in the removal of organics including pharmaceutical pollutants and drugs from wastewaters have been reported by [242-250]. Studies were mostly done in a laboratory scale because of high cost of UV source. Finding and developing cost effective alternatives to replace UV such as sun as a cheap source of light to generate efficient OH radicals will allow the potential of scale up for industrial large scale operations [251]. Additionally, mechanisms of transformation of organics in PMRs and the possibility to separate the reaction zone from the separation zone is not fully realized so far. Comprehensive studies are still required to determine these kind of mechanisms which have a great significance on the overall system performance[226, 251]. Innovation in the usage of nanoparticles immobilized in ceramic materials can further prevent photocatalyst degradation cause by irradiation and leads to a continuous operation in the system[251]. Figure 5 shows a schematic diagram of photocatalytic membrane reactor system with immersed UV-A lamps which is used in Sarasidis et al.(2014) experiments [249].

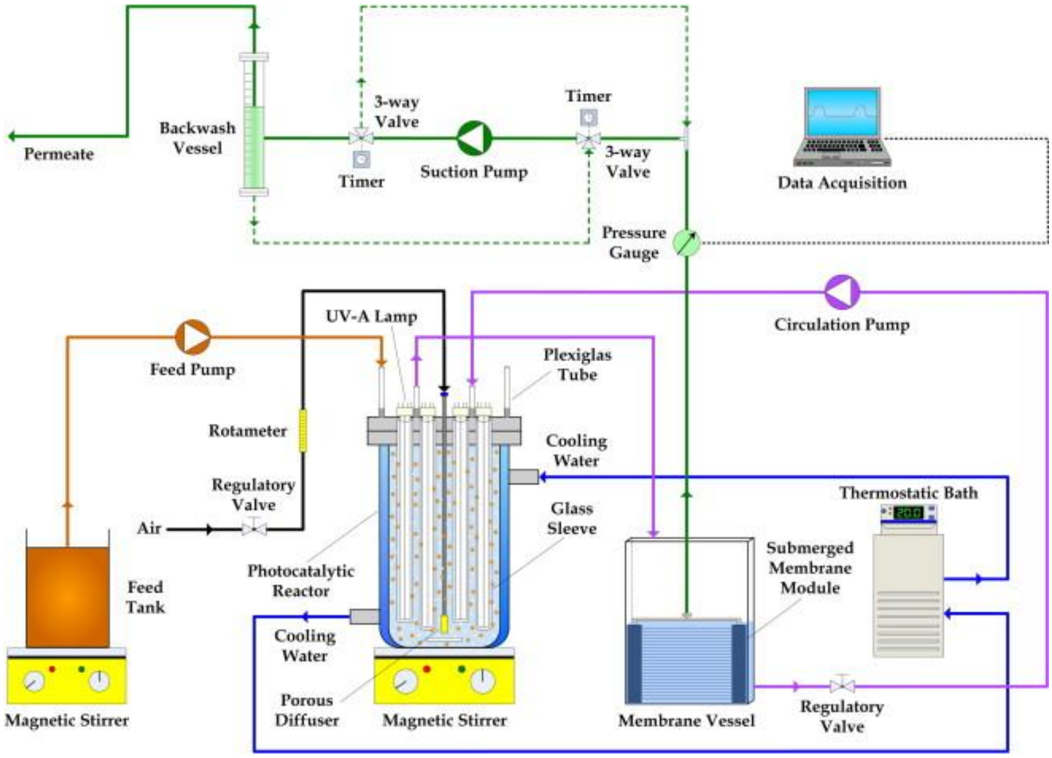

Fig 5. Photocatalytic membrane reactor with immersed UV-A lamps (reproduced from [249] with permission from the Chemical Engineering Journal)

Another promising combined configuration is electrochemical advanced oxidation processes (EAOPs) integrated with membrane modules as a hybrid reactor. Actually, the membrane unit has two roles in the system. It acts as electrode for electrochemical process and membrane for filtration [226]. From technical and economic point of view, this process seems to be a better choice compared to PMRs. it is capable of complete mineralization of persistent organics and production of high quality effluent because of generation of large quantities of hydroxyl radicals during the electrolysis. In addition, reactive electrochemical membranes do not require UV for OH generation and relatively inexpensive unlike PMRs [226]. However, industrial adoption of this technique depends on improved understanding of factors such as influence mechanism of organic and inorganic ions on performance of electrochemical membranes. Optimisation of operating parameters such as permeate flux, pressure, flow rate, pH and temperature leads to maximizing the efficiency of the hybrid system[226]. Introducing cost effective doping techniques to produce ceramics with high electrical conductivities seems to be a promising way for the production of electrode materials with high mechanical resistance which efficiently generate high yields of hydroxyl radicals [252-254].

5. Ceramic Membrane Cost analysis

It is very important to consider the type of application and fouling potential of feed wastewater for economic analysis of ceramic membranes. In terms of capital expenditure, commercially available ceramic membranes are three to 10 times more expensive than the polymeric membrane modules and hence many companies prefer polymeric option in their new installations [255, 256]; however, in aggressive operational environment the ceramic membrane may be a better alternative for wastewater filtration because of the remarkable reduction in operational costs. Normally the operating cost of an industrial scale membrane system is originated from the power and energy cost required to maintain a steady state long term permeate flux, the cost of membrane replacement, the cost of chemical and reagent required for membrane cleaning, and some of the costs such as worker's wages. Longer life span , ease of cleaning by high temperature steam sterilization and other potential unconventional method such as using electric and magnetic fields, and the ability to recover initial permeability and water flux by back flushing and proper cleaning, are all reasons that ceramic membranes have reduced operating cost than polymeric membranes [12]. Nanostone Water Inc. developed a ceramic versus polymeric cost model to estimate a total of 10 years' operating expenses based on pilot data collected from various industrial wastewater reuse plants using UF/MF membranes. Overall, the ceramic membrane reduced operating costs by 55 % [257]. Despite superior characteristics of ceramic membranes including high chemical, thermal and mechanical stability, ease of cleaning with various methods and longer lifespan, the high material cost of ceramic membranes which is around 500-2000 USD/m^2 compared to 50-400 USD/m^2 of polymeric membranes [255, 258-262], is the main drawback of applying this system in large scale industrial applications. The focus of future research should be in the development of cheap ceramics membrane for industrial applications including cheaper manufacturing and material costs. This could be achieved by incorporating new nanomaterials in membrane manufacturing technology. Utilizing engineered nanoceramic materials with improved hardness and mechanical and thermal strength for use in ceramic matrix composites will enhance the performance of ceramic membranes technically and economically. However, industrial scale application of nano-enabled ceramic membrane technology by industry may take years [263] because a lot of research need to be done to improve the current sintering methods [38].

6. Summary:

Ceramic membranes have outstanding features over polymeric membranes because of their remarkable robustness, ease of cleaning and high membrane life. However, there are still challenges in the application this technology for industrial effluents filtration that needs to be addressed in future researches. From the previous literature review conducted, it is deduced that the number of industrial scale application for the treatment of industrial effluents by ceramic membranes in comparison with laboratory investigations is very limited. This is due to its high capital cost, which encourages the industry shareholders to use polymeric systems for their liquid filtration purposes. Reducing ceramic membranes investment cost by introducing new fabrication processes will most likely make ceramic membranes an economically competitive alternative to polymeric membranes for many industrial scale applications. In the future, developing Ceramic nanofilters with lower MWCOs and with the ability to control pore size distribution may offer significant advantages in certain operating cases such as recovery of valuable materials in various industrial sections. Introduction of advanced sintering methods with low sintering temperature and short sintering times for the fabrication of nanoceramics can prevent the decomposition of ceramics, which will consequently lead to enhancing mechanical properties of ceramics as well as financial saving. Extensive studies are still required to improve AOPs by ceramic membrane reactors. Minimizing toxicity issue associated with ozone generation, developing cost-effective ceramic membranes with high resistance against irradiation to apply in photocatalytic ceramic membrane reactors, and producing ceramics with high electrical conductivity to apply as reactive electrochemical ceramic membranes in a hybrid reactor are some suggestions for future research and development in this category.

From the review of past studies, it can be concluded that the number of investigations done by ceramic membranes in the mining and pharmaceutical sections is more limited in comparison to the other industry sectors. This may be due to the complex nature of pharmaceutical wastewaters and AMD. Future research efforts should focus on further investigation of the application of various ceramic membranes with different pore sizes either alone or in combination with other physico-chemical techniques in treatment of pharmaceutical and mining effluents to guarantee steady state long-term operations without any or minimum requirement for membrane replacement.

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References:

[1] T. Mushiri, K. Manjengwa, C. Mbohwa, Advanced Fuzzy Control in Industrial Wastewater Treatment (pH and Temperature Control), in: Proceedings of the World Congress on Engineering, 2014.

[2] S. Hanchang, Industrial wastewater-types, amounts and effects, Point Sources of Pollution: Local Effects and their Control-Volume II, (2009) 191.

[3] S.A. Deowan, S.I. Bouhadjar, J. Hoinkis, Membrane bioreactors for water treatment, in: Advances in Membrane Technologies for Water Treatment, Woodhead Publishing, Oxford, 2015, pp. 155-184.

[4] T.T. More, S. Yan, R.D. Tyagi, R.Y. Surampalli, Applications of Membrane Processes for Concentrated Industrial Wastewater Treatment, in: Membrane Technology and Environmental Applications, 2012, pp. 217-238.

[5] R.W. Baker, Membrane technology and applications, John Wiley & Sons, Ltd, (2004) 96-103.

[6] S. Luque, D. Gómez, J.R. Álvarez, Industrial Applications of Porous Ceramic Membranes (Pressure-Driven Processes), in: Membrane Science and Technology, Elsevier, 2008, pp. 177-216.

[7] P. Sanciolo, S. Gray, Outcomes of membrane research: Impacts on the Australian and international water industry, in, Institute for Sustainability and Innovation Victoria University, 2014.

[8] A.K. Pabby, Handbook of Membrane Separations Chemical, Pharmaceutical, Food and Biotechnological Applications, Second Edition, 2nd ed.. ed., Hoboken, 2015.

[9] A.T. Fane, R. Wang, Y. Jia, Membrane technology: Past, present and future, in: Membrane and Desalination Technologies, Springer, 2011, pp. 1-45.

[10] I.G. Wenten, Recent development in membrane science and its industrial applications, J Sci Technol Membrane Sci Technol, 24 (2002) 1010-1024.

[11] Lenntech, Technical features of ceramic membranes - Lenntech http://www.lenntech.com/ceramic-membranes-features.htm Access Date:[09/08/2017], in, Rishi Sondhi, Ramesh Bhave and Gary Jung, 'Applications and benefits of ceramic membranes', Membrane Technology November 2003, 2017.

[12] M. Lee, Z. Wu, K. Li, Advances in ceramic membranes for water treatment, in: Advances in Membrane Technologies for Water Treatment, Woodhead Publishing, Oxford, 2015, pp. 43-82.

[13] B. Hofs, J. Ogier, D. Vries, E.F. Beerendonk, E.R. Cornelissen, Comparison of ceramic and polymeric membrane permeability and fouling using surface water, Separation and Purification Technology, 79 (2011) 365-374.

[14] S. Smart, C.X.C. Lin, L. Ding, K. Thambimuthu, J.C. Diniz da Costa, Ceramic membranes for gas processing in coal gasification, Energy & Environmental Science, 3 (2010) 268-278.

[15] V. Gitis, G. Rothenberg, Fundamentals of Membrane Separation, in: Ceramic Membranes: New Opportunities and Practical Applications, Wiley-VCH Verlag GmbH & Co. KGaA, 2016, pp. 91-148.

[16] B.T. C3 marketing agentur GmbH, Ceramic Filter Plates http://www.kerafol.com/en/filterkeramik/produkte/filterkeramikplatten/ Access Date : [15/02/2018].

[17] Tami Industries: Industrial Products http://www.tami-industries.com/en/industrial-products/industrial-products/ Acccess Date [14/02/2018].

[18] Ceradur http://www.i-2-m.com/dt_gallery/ceradur/ Access Date:[14/02/2018].

[19] Pall Corporation, Membralox® Ceramic Membrane Products - Whole Milk Concentration https://shop.pall.com/us/en/food-beverage/dairy/whole-milk-concentration/membralox-ceramic-membrane-products-zidgri78lwl?tracking=searchterm:hexagonal Access Date:[10/08/2017].

[20] Pall Corporation, Pall® Membralox® Ceramic Membranes and Modules - PIMEMBRAEN.pdf https://chemicals-polymers.pall.com/content/dam/pall/chemicals-polymers/literature-library/non-gated/PIMEMBRAEN.pdf Acccess Date:[10/08/2017].

[21] Veolia Water Technologies, About CeraMem® Ceramic Membrane Technology | Veolia Water Technologies http://technomaps.veoliawatertechnologies.com/ceramem/en/about-ceramem-technology.htm Access Date :[10/08/2017].

[22] Tami Industries, Tami Industries: Isoflux™ http://www.tami-industries.com/en/industrial-products/isofluxtm/ Access Date :[10/08/2017].

[23] Fraunhofer IGB, Membrane materials - Fraunhofer IGB http://www.igb.fraunhofer.de/en/research/competences/interfacial-materials/membranes/membrane-materials.html Access Date:[29/09/2017].

[24] Synder Filtration, Hollow Fiber Membranes http://synderfiltration.com/learning-center/articles/module-configurations-process/hollow-fiber-membranes/ Access Date:[19/09/2017].

[25] N.L. Le, S.P. Nunes, Materials and membrane technologies for water and energy sustainability, Sustainable Materials and Technologies, 7 (2016) 1-28.

[26] Tami Industries, Tami Industries: Industrial Products http://www.tami-industries.com/industrial-products/industrial-products/ Access Date:[30/08/2017].

[27] atech innovations gmbh, Technical data of atech Al_2O_3 membranes http://www.atech-innovations.com/fileadmin/downloads/atech_innovations_product_data_en.pdf Access Date [30/08/2017].

[28] Pall Corporation, Membralox® IC Ceramic Membranes and Modules - Drives Gear Box + Roll Housing https://shop.pall.com/us/en/industrial-manufacturing/automotive/stamping/membralox-ic-ceramic-membranes-and-modules-zidgri78m4a Access Date:[25/09/2017].

[29] Pall Corporation, Membralox® Ceramic Membranes and Modules - Mining Wastewater https://shop.pall.com/us/en/industrial-manufacturing/mining/mining-wastewater/membralox-ceramic-membranes-and-modules-zidgri78m7c Access Date:[31/08/2017].

[30] Veolia Water Technologies, Full-size Ceramic Membranes from Veolia Water Technologies http://technomaps.veoliawatertechnologies.com/ceramem/en/full-size-modules-ceramem.htm Access Date :[31/08/2017].

[31] ItN Water Filtration, Ceramic Flat Membrane Technology Data Sheet http://www.itn-nanovation.com/sites/default/files/Product_Files/TechnologyDataSheet_CFM.pdf Access Date :[31/08/2017].

[32] Meidensha Corporation Ceramic flatsheet membrane system | Industrial wastewater treatment systems | Meidensha Corporation http://www.meidensha.com/products/water/prod_06/prod_06_01/index.html Acccess Date:[31/08/2017].

[33] LiqTech International, COMEM® CONDUIT http://liqtech.com/wp-content/uploads/2017/03/COMEM-CONDUIT_CoMem-Conduit-OD146mm-ID3-2016-2.pdf Access Date:[31/08/2017].

[34] LiqTech International, COMEM® http://liqtech.com/wp-content/uploads/2017/03/COMEM_CoMem-OD25mm-ID3-2016-2.pdf Access Date :[31/08/2017].

[35] Inopor, Datasheet Ceramic NF membranes http://inopor.com/images/documents/downloads/en/productsheet/datasheet-ceramic-nf-membranes.pdf Access Date:[31/08/2017].

[36] Cembrane, Cembrane | Clean Water for Life http://cembrane.com/wp-content/uploads/SiCFS-0151-DO-T-520.pdf Access Date :[31/08/2017].

[37] S. Duscher, Ceramic membranes in chemical and pharmaceutical applications, Ceramic Applications, 1 (2013) 19-23.

[38] K.A. Khalil, Advanced sintering of nano-ceramic materials, in: Ceramic Materials-Progress in Modern Ceramics, InTech, 2012.

[39] I.-H. Choi, I.-C. Kim, B.-R. Min, K.-H. Lee, Preparation and characterization of ultrathin alumina hollow fiber microfiltration membrane, Desalination, 193 (2006) 256-259.

[40] B.F.K. Kingsbury, K. Li, A morphological study of ceramic hollow fibre membranes, Journal of Membrane Science, 328 (2009) 134-140.

[41] B.F.K. Kingsbury, Z. Wu, K. Li, A morphological study of ceramic hollow fibre membranes: A perspective on multifunctional catalytic membrane reactors, Catalysis Today, 156 (2010) 306-315.

[42] S. Koonaphapdeelert, K. Li, Preparation and characterization of hydrophobic ceramic hollow fibre membrane, Journal of Membrane Science, 291 (2007) 70-76.

[43] T. Wang, Y. Zhang, G. Li, H. Li, Preparation and characterization of alumina hollow fiber membranes, Frontiers of Chemical Engineering in China, 3 (2009) 265-271.

[44] C.C. Wei, O.Y. Chen, Y. Liu, K. Li, Ceramic asymmetric hollow fibre membranes—One step fabrication process, Journal of Membrane Science, 320 (2008) 191-197.

[45] X. Tan, S. Liu, K. Li, Preparation and characterization of inorganic hollow fiber membranes, Journal of Membrane Science, 188 (2001) 87-95.

[46] Z. Wu, R. Faiz, T. Li, B.F.K. Kingsbury, K. Li, A controlled sintering process for more permeable ceramic hollow fibre membranes, Journal of Membrane Science, 446 (2013) 286-293.

[47] T. Li, X. Lu, B. Wang, Z. Wu, K. Li, D.J.L. Brett, P.R. Shearing, X-ray tomography-assisted study of a phase inversion process in ceramic hollow fiber systems – Towards practical structural design, Journal of Membrane Science, 528 (2017) 24-33.

[48] M. Lee, B. Wang, K. Li, New designs of ceramic hollow fibres toward broadened applications, Journal of Membrane Science, 503 (2016) 48-58.

[49] M. Lee, Z. Wu, R. Wang, K. Li, Micro-structured alumina hollow fibre membranes – Potential applications in wastewater treatment, Journal of Membrane Science, 461 (2014) 39-48.

[50] N. Abdullah, M.A. Rahman, M.H.D. Othman, A.F. Ismail, J. Jaafar, A.A. Aziz, Preparation and characterization of self-cleaning alumina hollow fiber membrane using the phase inversion and sintering technique, Ceramics International, 42 (2016) 12312-12322.

[51] X. Tan, N. Liu, B. Meng, S. Liu, Morphology control of the perovskite hollow fibre membranes for oxygen separation using different bore fluids, Journal of Membrane Science, 378 (2011) 308-318.

[52] D. Agrawal, Microwave sintering of ceramics, composites and metallic materials, and melting of glasses, Transactions of the Indian ceramic society, 65 (2006) 129-144.

[53] M. Oghbaei, O. Mirzaee, Microwave versus conventional sintering: A review of fundamentals, advantages and applications, Journal of Alloys and Compounds, 494 (2010) 175-189.

[54] J. Croquesel, D. Bouvard, J.-M. Chaix, C.P. Carry, S. Saunier, S. Marinel, Direct microwave sintering of pure alumina in a single mode cavity: Grain size and phase transformation effects, Acta Materialia, 116 (2016) 53-62.

[55] Á. Presenda, M.D. Salvador, F.L. Penaranda-Foix, J.M. Catalá-Civera, E. Pallone, J. Ferreira, A. Borrell, Effects of microwave sintering in aging resistance of zirconia-based ceramics, Chemical Engineering and Processing: Process Intensification, (2017).

[56] M. Suárez, A. Fernández, J. Menéndez, R. Torrecillas, H. Kessel, J. Hennicke, R. Kirchner, T. Kessel, Challenges and opportunities for spark plasma sintering: a key technology for a new generation of materials, in: Sintering Applications, InTech, 2013.

[57] Z.-H. Zhang, Z.-F. Liu, J.-F. Lu, X.-B. Shen, F.-C. Wang, Y.-D. Wang, The sintering mechanism in spark plasma sintering – Proof of the occurrence of spark discharge, Scripta Materialia, 81 (2014) 56-59.

[58] R. Marder, C. Estournès, G. Chevallier, R. Chaim, Plasma in spark plasma sintering of ceramic particle compacts, Scripta Materialia, 82 (2014) 57-60.

[59] E.A. Olevsky, S.M. Rolfing, A.L. Maximenko, Flash (Ultra-Rapid) Spark-Plasma Sintering of Silicon Carbide, 6 (2016) 33408.

[60] K.A. Khalil, A.A. Almajid, Effect of high-frequency induction heat sintering conditions on the microstructure and mechanical properties of nanostructured magnesium/hydroxyapatite nanocomposites, Materials & Design (1980-2015), 36 (2012) 58-68.

[61] B. Jamal Abbasi, M. Zakeri, S.A. Tayebifard, High frequency induction heated sintering of nanostructured Al_2O_3–ZrB_2 composite produced by MASHS technique, Ceramics International, 40 (2014) 9217-9224.

[62] S. Won Kim, K. Abdel-Razek Khalil, S. The American Ceramic, High-Frequency Induction Heat Sintering of Mechanically Alloyed Alumina–Yttria-Stabilized Zirconia Nano-Bioceramics, in: Progress in Nanotechnology, John Wiley & Sons, Inc., 2009, pp. 79-84.

[63] S.A. Adeodun, Impact of Industrial Effluent on the Environment, (2016).

[64] D. Pokhrel, T. Viraraghavan, Treatment of pulp and paper mill wastewater—a review, Science of The Total Environment, 333 (2004) 37-58.

[65] K.-H. Ahn, H.-Y. Cha, I.-T. Yeom, K.-G. Song, Application of nanofiltration for recycling of paper regeneration wastewater and characterization of filtration resistance, Desalination, 119 (1998) 169-176.

[66] Z. Beril Gönder, S. Arayici, H. Barlas, Advanced treatment of pulp and paper mill wastewater by nanofiltration process: Effects of operating conditions on membrane fouling, Separation and Purification Technology, 76 (2011) 292-302.

[67] S. Ciputra, A. Antony, R. Phillips, D. Richardson, G. Leslie, Comparison of treatment options for removal of recalcitrant dissolved organic matter from paper mill effluent, Chemosphere, 81 (2010) 86-91.

[68] R. Ordóñez, D. Hermosilla, I.S. Pío, Á. Blanco, Evaluation of MF and UF as pretreatments prior to RO applied to reclaim municipal wastewater for freshwater substitution in a paper mill: A practical experience, Chemical Engineering Journal, 166 (2011) 88-98.

[69] R. Quezada, C.M. Silva, A.A.P. Rezende, L. Nilsson, M. Manfredi, Membrane treatment of the bleaching plant (EPO) filtrate of a kraft pulp mill, Water Science and Technology, 70 (2014) 843-850.

[70] M. Mänttäri, M. Kallioinen, M. Nyström, Membrane technologies for water treatment and reuse in the pulp and paper industries, in: Advances in Membrane Technologies for Water Treatment, Woodhead Publishing, Oxford, 2015, pp. 581-603.

[71] L. Puro, M. Kallioinen, M. Mänttäri, G. Natarajan, D. C. Cameron, M. Nyström, Performance of RC and PES ultrafiltration membranes in filtration of pulp mill process waters, Desalination, 264 (2010) 249-255.

[72] J.J. Gilman, The nature of ceramics, Scientific American, 217 (1967) 112-124.

[73] S.K. Nataraj, S. Sridhar, I.N. Shaikha, D.S. Reddy, T.M. Aminabhavi, Membrane-based microfiltration/electrodialysis hybrid process for the treatment of paper industry wastewater, Separation and Purification Technology, 57 (2007) 185-192.

[74] M. Ebrahimi, N. Busse, S. Kerker, O. Schmitz, M. Hilpert, P. Czermak, Treatment of the bleaching effluent from sulfite pulp production by ceramic membrane filtration, Membranes, 6 (2015) 7.

[75] A. Arkell, J. Olsson, O. Wallberg, Process performance in lignin separation from softwood black liquor by membrane filtration, Chemical Engineering Research and Design, 92 (2014) 1792-1800.

[76] A. Dafinov, J. Font, R. Garcia-Valls, Processing of black liquors by UF/NF ceramic membranes, Desalination, 173 (2005) 83-90.

[77] A. Keyoumu, R. Sjödahl, G. Henriksson, M. Ek, G. Gellerstedt, M.E. Lindström, Continuous nano- and ultra-filtration of kraft pulping black liquor with ceramic filters, Industrial Crops and Products, 20 (2004) 143-150.

[78] A.-S. Jönsson, A.-K. Nordin, O. Wallberg, Concentration and purification of lignin in hardwood kraft pulping liquor by ultrafiltration and nanofiltration, Chemical Engineering Research and Design, 86 (2008) 1271-1280.

[79] A. Holmqvist, O. Wallberg, A.S. Jönsson, Ultrafiltration of Kraft Black Liquor from Two Swedish Pulp Mills, Chemical Engineering Research and Design, 83 (2005) 994-999.

[80] O. Wallberg, A.-S. Jönsson, Influence of the membrane cut-off during ultrafiltration of kraft black liquor with ceramic membranes, Chemical Engineering Research and Design, 81 (2003) 1379-1384.

[81] O. Wallberg, M. Linde, A.-S. Jönsson, Extraction of lignin and hemicelluloses from kraft black liquor, Desalination, 199 (2006) 413-414.

[82] R. Ziesig, P. Tomani, H. Theliander, Production of a pure lignin product Part 2: Separation of lignin from membrane filtration Permeates of black liquor, Cellul. Chem. Technol, 48 (2014) 805-811.

[83] A. Toledano, A. García, I. Mondragon, J. Labidi, Lignin separation and fractionation by ultrafiltration, Separation and Purification Technology, 71 (2010) 38-43.

[84] G. Liu, Y. Liu, J. Ni, H. Shi, Y. Qian, Treatability of kraft spent liquor by microfiltration and andultrafiltration, Desalination, 160 (2004) 131-141.

[85] C.A.E. Costa, P.C.R. Pinto, A.E. Rodrigues, Lignin fractionation from E. Globulus kraft liquor by ultrafiltration in a three stage membrane sequence, Separation and Purification Technology, 192 (2018) 140-151.

[86] M. Žabková, E.A.B. da Silva, A.E. Rodrigues, Recovery of vanillin from lignin/vanillin mixture by using tubular ceramic ultrafiltration membranes, Journal of Membrane Science, 301 (2007) 221-237.

[87] M. Pizzichini, C. Russo, C.D. Meo, Purification of pulp and paper wastewater, with membrane technology, for water reuse in a closed loop, Desalination, 178 (2005) 351-359.

[88] D. Humpert, M. Ebrahimi, P. Czermak, Membrane Technology for the Recovery of Lignin: A Review, Membranes, 6 (2016) 42.

[89] Tami Industries, Tami Industries: Paper http://www.tami-industries.com/applications/environment/paper/#centre Access Date:[16/08/2017].

[90] V. Gitis, G. Rothenberg, Economics, in: Ceramic Membranes: New Opportunities and Practical Applications, Wiley-VCH Verlag GmbH & Co. KGaA, 2016, pp. 355-388.

[91] M.D. Afonso, M.N. De Pinho, Membrane separation processes in the pulp and paper industry, Desalination, 85 (1991) 53-58.

[92] A. Ghaly, R. Ananthashankar, M. Alhattab, V. Ramakrishnan, Production, characterization and treatment of textile effluents: a critical review, Journal of Chemical Engineering & Process Technology, 5 (2014) 1.

[93] I. Petrinić, N. Bajraktari, C. Hélix-Nielsen, Membrane technologies for water treatment and reuse in the textile industry, in: Advances in Membrane Technologies for Water Treatment, Woodhead Publishing, Oxford, 2015, pp. 537-550.

[94] P.C. Vandevivere, R. Bianchi, W. Verstraete, Review: Treatment and reuse of wastewater from the textile wet-processing industry: Review of emerging technologies, Journal of Chemical Technology and Biotechnology, 72 (1998) 289-302.

[95] P. Schoeberl, M. Brik, R. Braun, W. Fuchs, Treatment and recycling of textile wastewater —case study and development of a recycling concept, Desalination, 171 (2005) 173-183.

[96] J.M. Arnal, M.C. León, J. Lora, J.M. Gozálvez, A. Santafé, D. Sanz, J. Tena, Ultrafiltration as a pre-treatment of other membrane technologies in the reuse of textile wastewaters, Desalination, 221 (2008) 405-412.

[97] J.M. Gozálvez-Zafrilla, D. Sanz-Escribano, J. Lora-García, M.C. León Hidalgo, Nanofiltration of secondary effluent for wastewater reuse in the textile industry, Desalination, 222 (2008) 272-279.

[98] D.Y. Koseoglu-Imer, The determination of performances of polysulfone (PS) ultrafiltration membranes fabricated at different evaporation temperatures for the pretreatment of textile wastewater, Desalination, 316 (2013) 110-119.

[99] A. Akbari, J.C. Remigy, P. Aptel, Treatment of textile dye effluent using a polyamide-based nanofiltration membrane, Chemical Engineering and Processing: Process Intensification, 41 (2002) 601-609.

[100] I. Petrinić, N.P.R. Andersen, S. Šostar-Turk, A.M. Le Marechal, The removal of reactive dye printing compounds using nanofiltration, Dyes and Pigments, 74 (2007) 512-518.

[101] C. Tang, V. Chen, Nanofiltration of textile wastewater for water reuse, Desalination, 143 (2002) 11-20.

[102] M. Liu, Z. Lü, Z. Chen, S. Yu, C. Gao, Comparison of reverse osmosis and nanofiltration membranes in the treatment of biologically treated textile effluent for water reuse, Desalination, 281 (2011) 372-378.

[103] C. Fersi, M. Dhahbi, Treatment of textile plant effluent by ultrafiltration and/or nanofiltration for water reuse, Desalination, 222 (2008) 263-271.

[104] S.K. Nataraj, K.M. Hosamani, T.M. Aminabhavi, Nanofiltration and reverse osmosis thin film composite membrane module for the removal of dye and salts from the simulated mixtures, Desalination, 249 (2009) 12-17.

[105] A. Aouni, C. Fersi, M. Ben Sik Ali, M. Dhahbi, Treatment of textile wastewater by a hybrid electrocoagulation/nanofiltration process, Journal of Hazardous Materials, 168 (2009) 868-874.

[106] Z. Badani, H. Ait-Amar, A. Si-Salah, M. Brik, W. Fuchs, Treatment of textile waste water by membrane bioreactor and reuse, Desalination, 185 (2005) 411-417.

[107] T.V. Luong, S. Schmidt, S.A. Deowan, J. Hoinkis, A. Figoli, F. Galiano, Membrane Bioreactor and Promising Application for Textile Industry in Vietnam, Procedia CIRP, 40 (2016) 419-424.

[108] M. Brik, P. Schoeberl, B. Chamam, R. Braun, W. Fuchs, Advanced treatment of textile wastewater towards reuse using a membrane bioreactor, Process Biochemistry, 41 (2006) 1751-1757.

[109] Z. Lewandowski, H. Beyenal, Biofilms: their structure, activity, and effect on membrane filtration, Water science and technology : a journal of the International Association on Water Pollution Research, 51 (2005) 181-192.

[110] D. De Jager, M.S. Sheldon, W. Edwards, Colour removal from textile wastewater using a pilot-scale dual-stage MBR and subsequent RO system, Separation and Purification Technology, 135 (2014) 135-144.

[111] E. Sahinkaya, A. Yurtsever, Ö. Çınar, Treatment of textile industry wastewater using dynamic membrane bioreactor: Impact of intermittent aeration on process performance, Separation and Purification Technology, 174 (2017) 445-454.

[112] B. Van der Bruggen, B. Daems, D. Wilms, C. Vandecasteele, Mechanisms of retention and flux decline for the nanofiltration of dye baths from the textile industry, Separation and Purification Technology, 22 (2001) 519-528.

[113] J. Lin, W. Ye, H. Zeng, H. Yang, J. Shen, S. Darvishmanesh, P. Luis, A. Sotto, B. Van der Bruggen, Fractionation of direct dyes and salts in aqueous solution using loose nanofiltration membranes, Journal of Membrane Science, 477 (2015) 183-193.

[114] J. Zhu, M. Tian, Y. Zhang, H. Zhang, J. Liu, Fabrication of a novel "loose" nanofiltration membrane by facile blending with Chitosan–Montmorillonite nanosheets for dyes purification, Chemical Engineering Journal, 265 (2015) 184-193.

[115] F. Liu, B.-r. Ma, D. Zhou, L.-J. Zhu, Y.-Y. Fu, L.-x. Xue, Positively charged loose nanofiltration membrane grafted by diallyl dimethyl ammonium chloride (DADMAC) via UV for salt and dye removal, Reactive and Functional Polymers, 86 (2015) 191-198.

[116] J. Lin, W. Ye, M.-C. Baltaru, Y.P. Tang, N.J. Bernstein, P. Gao, S. Balta, M. Vlad, A. Volodin, A. Sotto, P. Luis, A.L. Zydney, B. Van der Bruggen, Tight ultrafiltration membranes for enhanced separation of dyes and Na2SO4 during textile wastewater treatment, Journal of Membrane Science, 514 (2016) 217-228.

[117] E. Alventosa-deLara, S. Barredo-Damas, M.I. Alcaina-Miranda, M.I. Iborra-Clar, Ultrafiltration technology with a ceramic membrane for reactive dye removal: Optimization of membrane performance, Journal of Hazardous Materials, 209–210 (2012) 492-500.

[118] X. Ma, P. Chen, M. Zhou, Z. Zhong, F. Zhang, W. Xing, Tight Ultrafiltration Ceramic Membrane for Separation of Dyes and Mixed Salts (both NaCl/Na2SO4) in Textile Wastewater Treatment, Industrial & Engineering Chemistry Research, 56 (2017) 7070-7079.

[119] S. Barredo-Damas, M.I. Alcaina-Miranda, A. Bes-Piá, M.I. Iborra-Clar, A. Iborra-Clar, J.A. Mendoza-Roca, Ceramic membrane behavior in textile wastewater ultrafiltration, Desalination, 250 (2010) 623-628.

[120] M. Zebić Avdičević, K. Košutić, S. Dobrović, Effect of operating conditions on the performances of multichannel ceramic UF membranes for textile mercerization wastewater treatment, Environmental Technology, 38 (2017) 65-77.

[121] E. Zuriaga-Agustí, E. Alventosa-deLara, S. Barredo-Damas, M.I. Alcaina-Miranda, M.I. Iborra-Clar, J.A. Mendoza-Roca, Performance of ceramic ultrafiltration membranes and fouling behavior of a dye-polysaccharide binary system, Water Research, 54 (2014) 199-210.

[122] R.C.O. Lima, H. Lira, G. Neves, M. Silva, K. França, Use of ceramic membrane for indigo separation in effluent from textile industry, in: Materials Science Forum, Trans Tech Publ, 2014, pp. 537-541.

[123] I. Jedidi, S. Khemakhem, S. Saïdi, A. Larbot, N. Elloumi-Ammar, A. Fourati, A. Charfi, A.B. Salah, R.B. Amar, Preparation of a new ceramic microfiltration membrane from mineral coal fly ash: Application to the treatment of the textile dying effluents, Powder Technology, 208 (2011) 427-432.

[124] P. Bhattacharya, S. Dutta, S. Ghosh, S. Vedajnananda, S. Bandyopadhyay, Crossflow microfiltration using ceramic membrane for treatment of sulphur black effluent from garment processing industry, Desalination, 261 (2010) 67-72.

[125] E. Alventosa-deLara, S. Barredo-Damas, E. Zuriaga-Agustí, M.I. Alcaina-Miranda, M.I. Iborra-Clar, Ultrafiltration ceramic membrane performance during the treatment of model solutions containing dye and salt, Separation and Purification Technology, 129 (2014) 96-105.

[126] A. Oun, N. Tahri, S. Mahouche-Chergui, B. Carbonnier, S. Majumdar, S. Sarkar, G.C. Sahoo, R. Ben Amar, Tubular ultrafiltration ceramic membrane based on titania nanoparticles immobilized on macroporous clay-alumina support: Elaboration, characterization and application to dye removal, Separation and Purification Technology, 188 (2017) 126-133.

[127] Pall Corporation, Membralox® Ceramic Membrane Bio-Reactor for Industrial Wastewater Treatment - CSMEMBRALOXEN.pdf https://chemicals-polymers.pall.com/content/dam/pall/chemicals-polymers/literature-library/non-gated/CSMEMBRALOXEN.pdf Access Date:[16/08/2017].

[128] Y. Ji, Membrane technologies for water treatment and reuse in the gas and petrochemical industries, in: Advances in Membrane Technologies for Water Treatment, Woodhead Publishing, Oxford, 2015, pp. 519-536.

[129] M. Padaki, R.S. Murali, M. Abdullah, N. Misdan, A. Moslehyani, M. Kassim, N. Hilal, A. Ismail, Membrane technology enhancement in oil–water separation. A review, Desalination, 357 (2015) 197-207.

[130] S.S. Madaeni, H. Ahmadi Monfared, V. Vatanpour, A. Arabi Shamsabadi, E. Salehi, P. Daraei, S. Laki, S.M. Khatami, Coke removal from petrochemical oily wastewater using γ-Al_2O_3 based ceramic microfiltration membrane, Desalination, 293 (2012) 87-93.

[131] E. Salehi, S.S. Madaeni, A.A. Shamsabadi, S. Laki, Applicability of ceramic membrane filters in pretreatment of coke-contaminated petrochemical wastewater: Economic feasibility study, Ceramics International, 40 (2014) 4805-4810.

[132] R. Ghidossi, D. Veyret, J.L. Scotto, T. Jalabert, P. Moulin, Ferry oily wastewater treatment, Separation and Purification Technology, 64 (2009) 296-303.

[133] S.R.H. Abadi, M.R. Sebzari, M. Hemati, F. Rekabdar, T. Mohammadi, Ceramic membrane performance in microfiltration of oily wastewater, Desalination, 265 (2011) 222-228.

[134] Y. Yang, R. Chen, W. Xing, Integration of ceramic membrane microfiltration with powdered activated carbon for advanced treatment of oil-in-water emulsion, Separation and Purification Technology, 76 (2011) 373-377.

[135] T. Yang, Z.-F. Ma, Q.-Y. Yang, Formation and performance of Kaolin/MnO_2 bi-layer composite dynamic membrane for oily wastewater treatment: Effect of solution conditions, Desalination, 270 (2011) 50-56.

[136] M. Abbasi, M. Mirfendereski, M. Nikbakht, M. Golshenas, T. Mohammadi, Performance study of mullite and mullite–alumina ceramic MF membranes for oily wastewaters treatment, Desalination, 259 (2010) 169-178.

[137] B.K. Nandi, A. Moparthi, R. Uppaluri, M.K. Purkait, Treatment of oily wastewater using low cost ceramic membrane: Comparative assessment of pore blocking and artificial neural network models, Chemical Engineering Research and Design, 88 (2010) 881-892.

[138] N.A. Ochoa, M. Masuelli, J. Marchese, Effect of hydrophilicity on fouling of an emulsified oil wastewater with PVDF/PMMA membranes, Journal of Membrane Science, 226 (2003) 203-211.

[139] M. Ulbricht, Advanced functional polymer membranes, Polymer, 47 (2006) 2217-2262.

[140] J.A. Howell, R.W. Field, D. Wu, Yeast cell microfiltration: Flux enhancement in baffled and pulsatile flow systems, Journal of Membrane Science, 80 (1993) 59-71.

[141] S. Finnigan, J. Howell, The effect of pulsatile flow on ultrafiltration fluxes in a baffled tubular membrane system, Chemical engineering research & design, 67 (1989) 278-282.

[142] R.J. Wakeman, C.J. Williams, Additional techniques to improve microfiltration, Separation and Purification Technology, 26 (2002) 3-18.
[143] B.B. Gupta, J.A. Howell, D. Wu, R.W. Field, A helical baffle for cross-flow microfiltration, Journal of Membrane Science, 102 (1995) 31-42.

[144] S. Wroński, E. Molga, L. Rudniak, Dynamic filtration in biotechnology, Bioprocess Engineering, 4 (1989) 99-104.

[145] C.A. Serra, M.R. Wiesner, J.-M. Laîné, Rotating membrane disk filters: design evaluation using computational fluid dynamics, Chemical Engineering Journal, 72 (1999) 1-17.

[146] X. Chai, T. Kobayashi, N. Fujii, Ultrasound effect on cross-flow filtration of polyacrylonitrile ultrafiltration membranes, Journal of Membrane Science, 148 (1998) 129-135.

[147] A. Salahi, A. Gheshlaghi, T. Mohammadi, S.S. Madaeni, Experimental performance evaluation of polymeric membranes for treatment of an industrial oily wastewater, Desalination, 262 (2010) 235-242.

[148] A. Rahimpour, B. Rajaeian, A. Hosienzadeh, S.S. Madaeni, F. Ghoreishi, Treatment of oily wastewater produced by washing of gasoline reserving tanks using self-made and commercial nanofiltration membranes, Desalination, 265 (2011) 190-198.

[149] F. Sadeghi, M.R. Mehrnia, R. Nabizadeh, M.B. Bahadori, M.H. Sarrafzadeh, MBR technology: A practical approach for petrochemical wastewater treatment, Petroleum Science and Technology, 35 (2017) 222-228.

[150] S. Soltani, D. Mowla, M. Vossoughi, M. Hesampour, Experimental investigation of oily water treatment by membrane bioreactor, Desalination, 250 (2010) 598-600.

[151] L. Qin, Z. Fan, L. Xu, G. Zhang, G. Wang, D. Wu, X. Long, Q. Meng, A submerged membrane bioreactor with pendulum type oscillation (PTO) for oily wastewater treatment: Membrane permeability and fouling control, Bioresource Technology, 183 (2015) 33-41.

[152] T. Zsirai, A.K. Al-Jaml, H. Qiblawey, M. Al-Marri, A. Ahmed, S. Bach, S. Watson, S. Judd, Ceramic membrane filtration of produced water: Impact of membrane module, Separation and Purification Technology, 165 (2016) 214-221.

[153] S.E. Weschenfelder, M.J.C. Fonseca, C.P. Borges, J.C. Campos, Application of ceramic membranes for water management in offshore oil production platforms: Process design and economics, Separation and Purification Technology, 171 (2016) 214-220.

[154] Y. Lester, I. Ferrer, E.M. Thurman, K.A. Sitterley, J.A. Korak, G. Aiken, K.G. Linden, Characterization of hydraulic fracturing flowback water in Colorado: Implications for water treatment, Science of The Total Environment, 512 (2015) 637-644.

[155] Veolia Water Technologies, ROSS™ System | Frac Flowback and Produced Water Treatment http://www.veoliawatertech.com/en/news-resources/datasheets/ross-flowback-produced-water.htm Access Date :[10/09/2017].

[156] Veolia Water Technologies, CeraMem® Ceramic Membrane Technology | Veolia Water Technologies http://technomaps.veoliawatertechnologies.com/ceramem/en/ Access Date [28/09/2017], (2017).
[157] A. Cassano, N.K. Rastogi, A. Basile, Membrane technologies for water treatment and reuse in the food and beverage industries, in: Advances in Membrane Technologies for Water Treatment, Woodhead Publishing, Oxford, 2015, pp. 551-580.

[158] S. Casani, M. Rouhany, S. Knøchel, A discussion paper on challenges and limitations to water reuse and hygiene in the food industry, Water Research, 39 (2005) 1134-1146.

[159] W. Qasim, A.V. Mane, Characterization and treatment of selected food industrial effluents by coagulation and adsorption techniques, Water Resources and Industry, 4 (2013) 1-12.

[160] R.V. Kumar, L. Goswami, K. Pakshirajan, G. Pugazhenthi, Dairy wastewater treatment using a novel low cost tubular ceramic membrane and membrane fouling mechanism using pore blocking models, Journal of Water Process Engineering, 13 (2016) 168-175.

[161] M.R. Hart, C.C. Huxsoll, L.-S. Tsai, K.C. Ng, Preliminary Studies of Microfiltration for Food Processing Water Reuse 1, Journal of Food Protection, 51 (1988) 269-276.

[162] N. Değermenci, İ. Cengiz, E. Yildiz, A. Nuhoglu, Performance investigation of a jet loop membrane bioreactor for the treatment of an actual olive mill wastewater, Journal of Environmental Management, 184, Part 2 (2016) 441-447.

[163] M. Li, Y. Zhao, S. Zhou, W. Xing, Clarification of raw rice wine by ceramic microfiltration membranes and membrane fouling analysis, Desalination, 256 (2010) 166-173.

[164] C. Almandoz, C. Pagliero, A. Ochoa, J. Marchese, Corn syrup clarification by microfiltration with ceramic membranes, Journal of Membrane Science, 363 (2010) 87-95.

[165] M. Li, Y. Zhao, S. Zhou, W. Xing, F.-S. Wong, Resistance analysis for ceramic membrane microfiltration of raw soy sauce, Journal of Membrane Science, 299 (2007) 122-129.

[166] M. Kuca, D. Szaniawska, Application of microfiltration and ceramic membranes for treatment of salted aqueous effluents from fish processing, Desalination, 241 (2009) 227-235.

[167] M.D. Afonso, R. Bórquez, Review of the treatment of seafood processing wastewaters and recovery of proteins therein by membrane separation processes — prospects of the ultrafiltration of wastewaters from the fish meal industry, Desalination, 142 (2002) 29-45.

[168] M. Diná Afonso, J. Ferrer, R. Bórquez, An economic assessment of proteins recovery from fish meal effluents by ultrafiltration, Trends in Food Science & Technology, 15 (2004) 506-512.

[169] K. Walha, R. Ben Amar, A. Massé, P. Bourseau, M. Cardinal, J. Cornet, C. Prost, P. Jaouen, Aromas potentiality of tuna cooking juice concentrated by nanofiltration, LWT - Food Science and Technology, 44 (2011) 153-157.

[170] F. Rögener, V. Mavrov, H. Chmiel, Treatment of Rinsing Water from Bottle Washing Machines by Membrane Filtration with the Objective of Reuse, Engineering in Life Sciences, 3 (2003) 218-225.

[171] S. Emani, R. Uppaluri, M.K. Purkait, Preparation and characterization of low cost ceramic membranes for mosambi juice clarification, Desalination, 317 (2013) 32-40.

[172] L.R. Fukumoto, P. Delaquis, B. Girard, Microfiltration and Ultrafiltration Ceramic Membranes for Apple Juice Clarification, Journal of Food Science, 63 (1998) 845-850.

[173] Q. Gan, J.A. Howell, R.W. Field, R. England, M.R. Bird, M.T. McKechinie, Synergetic cleaning procedure for a ceramic membrane fouled by beer microfiltration, Journal of Membrane Science, 155 (1999) 277-289.

[174] A. Hinkova, Z. Bubník, P. Kadlec, J. Pridal, Potentials of separation membranes in the sugar industry, Separation and Purification Technology, 26 (2002) 101-110.

[175] W. Li, G. Ling, F. Lei, N. Li, W. Peng, K. Li, H. Lu, F. Hang, Y. Zhang, Ceramic membrane fouling and cleaning during ultrafiltration of limed sugarcane juice, Separation and Purification Technology, 190 (2018) 9-24.

[176] F.P. Cuperus, Membrane processes in agro-food: State-of-the-art and new opportunities, Separation and Purification Technology, 14 (1998) 233-239.

[177] M. Turan, I. Koyuncu, D. Topacik, A. Ateş, Comparative evaluation of nanofiltration and reverse osmosis treatment of an effluent from dairy industry, Journal of Environmental Science and Health, Part A, 35 (2000) 741-754.

[178] V. Yip, S.D. Arntfield, A.W. Hydamaka, Potential for Stainless Steel Microfiltration Processing to Reduce Effluent from a Fluid Milk and Ice Cream Processing Plant, Journal of Dairy Science, 79 (1996) 710-716.

[179] C.F. Bennani, B. Ousji, D.J. Ennigrou, Reclamation of dairy wastewater using ultrafiltration process, Desalination and Water Treatment, 55 (2015) 297-303.

[180] M. Skrzypek, M. Burger, Isoflux® ceramic membranes — Practical experiences in dairy industry, Desalination, 250 (2010) 1095-1100.

[181] G. Brans, C.G.P.H. Schroën, R.G.M. van der Sman, R.M. Boom, Membrane fractionation of milk: state of the art and challenges, Journal of Membrane Science, 243 (2004) 263-272.

[182] L. Fernández García, S. Álvarez Blanco, F.A. Riera Rodríguez, Microfiltration applied to dairy streams: removal of bacteria, Journal of the Science of Food and Agriculture, 93 (2013) 187-196.

[183] P. Bolduan, M. Latz, Filtration by Means of Ceramic Membranes - Practical Examples from the Chemical and Food Industries, in, atech innovations gmbh, 2017.

[184] G. Eriksson, Applied research for RO and UF, Process Biochemistry, Vol 9, No 2, P 18-19, February/March, 1974. 3 Fig, 2 Tab., (1974), (1974).

[185] D. Mancinelli, C. Hallé, Nano-Filtration and Ultra-Filtration Ceramic Membranes for Food Processing: A Mini Review, Journal of Membrane Science & Technology, 5 (2015) 1.

[186] M. Taheran, S.K. Brar, M. Verma, R.Y. Surampalli, T.C. Zhang, J.R. Valero, Membrane processes for removal of pharmaceutically active compounds (PhACs) from water and wastewaters, Science of The Total Environment, 547 (2016) 60-77.

[187] C. Gadipelly, A. Pérez-González, G.D. Yadav, I. Ortiz, R. Ibáñez, V.K. Rathod, K.V. Marathe, Pharmaceutical Industry Wastewater: Review of the Technologies for Water Treatment and Reuse, Industrial & Engineering Chemistry Research, 53 (2014) 11571-11592.

[188] K. Murdoch, Pharmaceutical Pollution in the Environment: Issues for Australia, New Zealand and Pacific Island countries, (2015).

[189] S.A. Snyder, S. Adham, A.M. Redding, F.S. Cannon, J. DeCarolis, J. Oppenheimer, E.C. Wert, Y. Yoon, Role of membranes and activated carbon in the removal of endocrine disruptors and pharmaceuticals, Desalination, 202 (2007) 156-181.

[190] Y. Yoon, P. Westerhoff, S.A. Snyder, E.C. Wert, J. Yoon, Removal of endocrine disrupting compounds and pharmaceuticals by nanofiltration and ultrafiltration membranes, Desalination, 202 (2007) 16-23.

[191] J. Radjenović, M. Petrović, F. Ventura, D. Barceló, Rejection of pharmaceuticals in nanofiltration and reverse osmosis membrane drinking water treatment, Water Research, 42 (2008) 3601-3610.

[192] X.-m. Wang, B. Li, T. Zhang, X.-y. Li, Performance of nanofiltration membrane in rejecting trace organic compounds: Experiment and model prediction, Desalination, 370 (2015) 7-16.

[193] R.M. Narbaitz, D. Rana, H.T. Dang, J. Morrissette, T. Matsuura, S.Y. Jasim, S. Tabe, P. Yang, Pharmaceutical and personal care products removal from drinking water by modified cellulose acetate membrane: Field testing, Chemical Engineering Journal, 225 (2013) 848-856.

[194] M.A. Boleda, M.A. Galceran, F. Ventura, Behavior of pharmaceuticals and drugs of abuse in a drinking water treatment plant (DWTP) using combined conventional and ultrafiltration and reverse osmosis (UF/RO) treatments, Environmental pollution (Barking, Essex : 1987), 159 (2011) 1584-1591.

[195] L.D. Nghiem, A.I. Schäfer, M. Elimelech, Pharmaceutical Retention Mechanisms by Nanofiltration Membranes, Environmental Science & Technology, 39 (2005) 7698-7705.

[196] T. Heberer, D. Feldmann, Removal of Pharmaceutical Residues from Contaminated Raw Water Sources by Membrane Filtration, in: K. Kümmerer (Ed.) Pharmaceuticals in the Environment: Sources, Fate, Effects and Risks, Springer Berlin Heidelberg, Berlin, Heidelberg, 2008, pp. 427-453.

[197] M. Bodzek, M. Dudziak, Elimination of steroidal sex hormones by conventional water treatment and membrane processes, Desalination, 198 (2006) 24-32.

[198] A. Shahtalebi, M. Sarrafzadeh, M.M. Rahmati, Application of nanofiltration membrane in the separation of amoxicillin from pharmaceutical wastewater, Iranian Journal of Environmental Health Science & Engineering, 8 (2011) 109.

[199] W. Zhang, G. He, P. Gao, G. Chen, Development and characterization of composite nanofiltration membranes and their application in concentration of antibiotics, Separation and Purification Technology, 30 (2003) 27-35.

[200] R.W. Baker, Membrane technology and applications, 3 ed., 2012.

[201] Hydro Air Research, Pharmaceutical | Hydro Air Research Italia https://www.hydair.com/pharmaceutical/ Access Date:[08/08/2017]

[202] Mantec Filtration, Case Study Star-Sep Ceramic Membranes | Mantec Filtration http://mantecfiltration.com/case-study-star-sep-ceramic-membranes/ Access Date[08/08/2017]

[203] C. Mitcham, Encyclopedia of science, technology, and ethics, Macmillan Reference USA, Detroit, MI, 2005.

[204] A. Akcil, S. Koldas, Acid Mine Drainage (AMD): causes, treatment and case studies, Journal of Cleaner Production, 14 (2006) 1139-1145.

[205] A. Peppas, K. Komnitsas, I. Halikia, Use of organic covers for acid mine drainage control, Minerals Engineering, 13 (2000) 563-574.

[206] C.-M. Zhong, Z.-L. Xu, X.-H. Fang, L. Cheng, Treatment of acid mine drainage (AMD) by ultra-low-pressure reverse osmosis and nanofiltration, Environmental Engineering Science, 24 (2007) 1297-1306.

[207] V. Bonnelye, Acid mine drainage : case study of one of the largest copper mine sites in thw world.

[208] H. Al-Zoubi, A. Rieger, P. Steinberger, W. Pelz, R. Haseneder, G. Härtel, Optimization Study for Treatment of Acid Mine Drainage Using Membrane Technology, Separation Science and Technology, 45 (2010) 2004-2016.

[209] K. Häyrynen, E. Pongrácz, V. Väisänen, N. Pap, M. Mänttäri, J. Langwaldt, R.L. Keiski, Concentration of ammonium and nitrate from mine water by reverse osmosis and nanofiltration, Desalination, 240 (2009) 280-289.

[210] M. Mullett, R. Fornarelli, D. Ralph, Nanofiltration of Mine Water: Impact of Feed pH and Membrane Charge on Resource Recovery and Water Discharge, Membranes, 4 (2014).

[211] C. Sierra, J.R.A. Saiz, J.L.R. Gallego, Nanofiltration of Acid Mine Drainage in an Abandoned Mercury Mining Area, Water Air Soil Pollut., 224 (2013) 12.

[212] R. Thiruvenkatachari, M. Francis, M. Cunnington, S. Su, Application of integrated forward and reverse osmosis for coal mine wastewater desalination, Separation and Purification Technology, 163 (2016) 181-188.

[213] L.H. Andrade, A.O. Aguiar, W.L. Pires, L.B. Grossi, M.C.S. Amaral, Comprehensive bench- and pilot-scale investigation of NF for gold mining effluent treatment: Membrane performance and fouling control strategies, Separation and Purification Technology, 174 (2017) 44-56.

[214] H.S. Al-Zoubi, S.S. Al-Thyabat, Treatment of a Jordanian Phosphate Mine Wastewater by Hybrid Dissolved Air Flotation and Nanofiltration, Mine Water and the Environment, 31 (2012) 214-224.

[215] M.O. Daramola, B. Silinda, S. Masondo, O.O. Oluwasina, Polyethersulphone-sodalite (PES-SOD) mixed-matrix membranes: prospects for acid mine drainage (AMD) treatment, J. S. Afr. Inst. Min. Metall., 115 (2015) 1221-1228.

[216] H. Koseoglu, M. Kitis, The recovery of silver from mining wastewaters using hybrid cyanidation and high-pressure membrane process, Minerals Engineering, 22 (2009) 440-444.

[217] A.L. Carvalho, F. Maugeri, P. Prádanos, V. Silva, A. Hernández, Separation of potassium clavulanate and potassium chloride by nanofiltration, Separation and Purification Technology, 83 (2011) 23-30.

[218] A.O. Aguiar, L.H. Andrade, B.C. Ricci, W.L. Pires, G.A. Miranda, M.C.S. Amaral, Gold acid mine drainage treatment by membrane separation processes: An evaluation of the main operational conditions, Separation and Purification Technology, 170 (2016) 360-369.

[219] R. Fornarelli, M. Mullett, D. Ralph, Factors influencing nanofiltration of acid mine drainage, (2013).

[220] D.R. Stewart, Water Filtration Innovation to Optimize Recovery and Lower TCO, (2013).

[221] Tetra Tech, Final Remedial Investigation Report,Upper Blackfoot Mining Complex Lewis and Clark County, Montana (2013).

[222] LiqTech, Heavy Metal Removal http://liqtech.com/wp-content/uploads/2017/01/Kundecase_Heavy-Metal-Removal_US.pdf Access Date:[31/08/2017].

[223] G.S. Simate, S. Ndlovu, Acid mine drainage: Challenges and opportunities, Journal of Environmental Chemical Engineering, 2 (2014) 1785-1803.

[224] J.A. Tuszyński, M.L.A. Nip, D. Sept, Nonlinear Modelling of Chemical Kinetics for the Acid Mine Drainage Problem and Related Physical Topics, University of Alberta, Department of Physics, 1994.

[225] K.-H. Choo, Advanced Oxidation Process (AOP) by Membrane Reactors, in: E. Drioli, L. Giorno (Eds.) Encyclopedia of Membranes, Springer Berlin Heidelberg, Berlin, Heidelberg, 2016, pp. 10-11.

[226] S.O. Ganiyu, E.D. van Hullebusch, M. Cretin, G. Esposito, M.A. Oturan, Coupling of membrane filtration and advanced oxidation processes for removal of pharmaceutical residues: A critical review, Separation and Purification Technology, 156 (2015) 891-914.

[227] R. Molinari, M. Mungari, E. Drioli, A. Di Paola, V. Loddo, L. Palmisano, M. Schiavello, Study on a photocatalytic membrane reactor for water purification, Catalysis Today, 55 (2000) 71-78.

[228] R. Molinari, C. Grande, E. Drioli, L. Palmisano, M. Schiavello, Photocatalytic membrane reactors for degradation of organic pollutants in water, Catalysis Today, 67 (2001) 273-279.

[229] Ozonation | SSWM https://www.sswm.info/content/ozonation Access Date:[16/08/2017].

[230] B.S. Oh, H.Y. Jang, T.M. Hwang, J.-W. Kang, Role of ozone for reducing fouling due to pharmaceuticals in MF (microfiltration) process, Journal of Membrane Science, 289 (2007) 178-186.

[231] B.S. Oh, H.Y. Jang, J. Cho, S. Lee, E. Lee, I.S. Kim, T.M. Hwang, J.-W. Kang, Effect of ozone on microfiltration as a pretreatment of seawater reverse osmosis, Desalination, 238 (2009) 90-97.
[232] G.R. Pophali, S. Hedau, N. Gedam, N.N. Rao, T. Nandy, Treatment of refractory organics from membrane rejects using ozonation, Journal of Hazardous Materials, 189 (2011) 273-277.

[233] T. Zhou, T.-T. Lim, S.-S. Chin, A.G. Fane, Treatment of organics in reverse osmosis concentrate from a municipal wastewater reclamation plant: Feasibility test of advanced oxidation processes with/without pretreatment, Chemical Engineering Journal, 166 (2011) 932-939.

[234] K. Liu, F.A. Roddick, L. Fan, Impact of salinity and pH on the UVC/H2O2 treatment of reverse osmosis concentrate produced from municipal wastewater reclamation, Water Research, 46 (2012) 3229-3239.

[235] A. Justo, O. González, J. Aceña, S. Pérez, D. Barceló, C. Sans, S. Esplugas, Pharmaceuticals and organic pollution mitigation in reclamation osmosis brines by UV/H2O2 and ozone, Journal of Hazardous Materials, 263 (2013) 268-274.

[236] L.Y. Lee, H.Y. Ng, S.L. Ong, J.Y. Hu, G. Tao, K. Kekre, B. Viswanath, W. Lay, H. Seah, Ozone-biological activated carbon as a pretreatment process for reverse osmosis brine treatment and recovery, Water Research, 43 (2009) 3948-3955.

[237] P. Liu, H. Zhang, Y. Feng, F. Yang, J. Zhang, Removal of trace antibiotics from wastewater: A systematic study of nanofiltration combined with ozone-based advanced oxidation processes, Chemical Engineering Journal, 240 (2014) 211-220.

[238] S. Heng, K.L. Yeung, A. Julbe, A. Ayral, J.-C. Schrotter, Preparation of composite zeolite membrane separator/contactor for ozone water treatment, Microporous and Mesoporous Materials, 115 (2008) 137-146.

[239] H.L. Ho, W.K. Chan, A. Blondy, K.L. Yeung, J.-C. Schrotter, Experiment and modeling of advanced ozone membrane reactor for treatment of organic endocrine disrupting pollutants in water, Catalysis Today, 193 (2012) 120-127.

[240] W. Kit Chan, J. Jouët, S. Heng, K. Lun Yeung, J.-C. Schrotter, Membrane contactor/separator for an advanced ozone membrane reactor for treatment of recalcitrant organic pollutants in water, Journal of Solid State Chemistry, 189 (2012) 96-100.

[241] S. Heng, K.L. Yeung, M. Djafer, J.-C. Schrotter, A novel membrane reactor for ozone water treatment, Journal of Membrane Science, 289 (2007) 67-75.

[242] R. Molinari, F. Pirillo, V. Loddo, L. Palmisano, Heterogeneous photocatalytic degradation of pharmaceuticals in water by using polycrystalline TiO2 and a nanofiltration membrane reactor, Catalysis Today, 118 (2006) 205-213.

[243] R. Molinari, A. Caruso, P. Argurio, T. Poerio, Degradation of the drugs Gemfibrozil and Tamoxifen in pressurized and de-pressurized membrane photoreactors using suspended polycrystalline TiO2 as catalyst, Journal of Membrane Science, 319 (2008) 54-63.

[244] V. Augugliaro, E. García-López, V. Loddo, S. Malato-Rodríguez, I. Maldonado, G. Marcì, R. Molinari, L. Palmisano, Degradation of lincomycin in aqueous medium: Coupling of solar photocatalysis and membrane separation, Solar Energy, 79 (2005) 402-408.

[245] T.E. Doll, F.H. Frimmel, Cross-flow microfiltration with periodical back-washing for photocatalytic degradation of pharmaceutical and diagnostic residues–evaluation of the long-term stability of the photocatalytic activity of TiO2, Water Research, 39 (2005) 847-854.

[246] M.J. Benotti, B.D. Stanford, E.C. Wert, S.A. Snyder, Evaluation of a photocatalytic reactor membrane pilot system for the removal of pharmaceuticals and endocrine disrupting compounds from water, Water Research, 43 (2009) 1513-1522.

[247] D.P. Ho, S. Vigneswaran, H.H. Ngo, Photocatalysis-membrane hybrid system for organic removal from biologically treated sewage effluent, Separation and Purification Technology, 68 (2009) 145-152.

[248] S. Mozia, A.W. Morawski, The performance of a hybrid photocatalysis–MD system for the treatment of tap water contaminated with ibuprofen, Catalysis Today, 193 (2012) 213-220.

[249] V.C. Sarasidis, K.V. Plakas, S.I. Patsios, A.J. Karabelas, Investigation of diclofenac degradation in a continuous photo-catalytic membrane reactor. Influence of operating parameters, Chemical Engineering Journal, 239 (2014) 299-311.

[250] D. Darowna, S. Grondzewska, A.W. Morawski, S. Mozia, Removal of non-steroidal anti-inflammatory drugs from primary and secondary effluents in a photocatalytic membrane reactor, Journal of Chemical Technology & Biotechnology, 89 (2014) 1265-1273.

[251] R. Molinari, C. Lavorato, P. Argurio, Recent progress of photocatalytic membrane reactors in water treatment and in synthesis of organic compounds. A review, Catalysis Today, 281 (2017) 144-164.

[252] I. Sirés, E. Brillas, M.A. Oturan, M.A. Rodrigo, M. Panizza, Electrochemical advanced oxidation processes: today and tomorrow. A review, Environmental Science and Pollution Research, 21 (2014) 8336-8367.

[253] B.P. Chaplin, Critical review of electrochemical advanced oxidation processes for water treatment applications, Environmental science. Processes & impacts, 16 (2014) 1182-1203.

[254] Y. Lin, Y. Cai, E. Drioli, Y. Fan, Enhancing mechanical and photocatalytic performances on TiO2/Ti composite ultrafiltration membranes via Ag doping method, Separation and Purification Technology, 145 (2015) 29-38.

[255] V. Gitis, G. Rothenberg, The Basics, in: Ceramic Membranes: New Opportunities and Practical Applications, Wiley-VCH Verlag GmbH & Co. KGaA, 2016, pp. 1-90.

[256] M. Howdeshel, R. Huang, Comparison of Ceramic and Polymeric Membranes in Wastewater Treatment.pdf, Siemens Industry, 2011.

[257] B.S. Al-anzi, O.C. Siang, Recent developments of carbon based nanomaterials and membranes for oily wastewater treatment, RSC Advances, 7 (2017) 20981-20994.

[258] V. Singh, N.K. Meena, A.K. Golder, C. Das, Fabrication of cost effective iron ore slime ceramic membrane for the recovery of organic solvent used in coke production, International Journal of Coal Science & Technology, 3 (2016) 226-234.
[259] W.J. Koros, R. Mahajan, Pushing the limits on possibilities for large scale gas separation: which strategies?, Journal of Membrane Science, 175 (2000) 181-196.

[260] B.D. Bhide, S.A. Stern, A new evaluation of membrane processes for the oxygen-enrichment of air. I. Identification of optimum operating conditions and process configuration, Journal of Membrane Science, 62 (1991) 13-35.

[261] S. Jana, M. Purkait, K. Mohanty, Preparation and characterization of low-cost ceramic microfiltration membranes for the removal of chromate from aqueous solutions, Applied Clay Science, 47 (2010) 317-324.

[262] B.K. Nandi, R. Uppaluri, M.K. Purkait, Preparation and characterization of low cost ceramic membranes for micro-filtration applications, Applied Clay Science, 42 (2008) 102-110.

[263] P.S. Goh, A.F. Ismail, N. Hilal, Nano-enabled membranes technology: Sustainable and revolutionary solutions for membrane desalination, Desalination, 380 (2016) 100-104.

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