Membrane Bioreactors in Tannery Wastewater Treatment: Sustainability and Challenges

Conference: 13th AICLST, Kolkata, 6–8 March 2026

Paper reference: TC-28/P

Printed pages: 332–342

Source: *Leather 2050: Challenges & Opportunities*, ILTA (2026)

Membrane Bioreactors in Tannery Wastewater Treatment:

Sustainability and Challenges

U. Sathya1*, Dinakaran2, M. Karthikeyam3

1Environmental Engineering Department, CSIR-Central Leather Research Institute

Sardar Patel Road, Adyar, Chennai 600 020, INDIA.

2,3Centre for Environmental Studies, CEG campus, Anna University, Chennai, India

Ref. No. TC-28/P

Abstract

Due to the limited fresh water sources and increased water demand in the tannery industry, a promising technology for treating tannery wastewater is the need to comply the current environmental regulations. Tannery wastewater is characterized by the presence of high concentrations of organic matter, sulphides, salinity, chromium, etc. Conventional treatment methods which involves many stages of operations such as secondary clarifier, tertiary treatment, etc. often facing challenges to achieve stringent standards due to their limited efficiency in the removal of pollutants and high operational footprint. Since the discharge standards of wastewater has noticeably becoming stringent in recent times, substantial advancements have been made in the tannery wastewater treatment technologies which focuses on the sustainable, efficient, and cost-effective systems. The integration of biological, physico-chemical with membrane-based processes offers improved pollutant removal with minimal stages of operations, reduced sludge generation, and improved water reuse potential. Membrane Bio Reactor (MBR) can be an innovative option for wastewater treatment in providing quality permeate which offers the reuse of treated wastewater. MBR can be advantage of achieving high retention of solid particles, elimination of secondary clarifier, and producing quality permeate. MBR can be used with higher Mixed Liquor

Corresponding author email : sathcivil@gmail.com / u-sathya@clri.res.in

Suspended Solids (MLSS) and can be increased upto 12000 mg/L. The MBR permeate which has SDI < 5, can be the best feed for RO treatment so that the reuse of treated tannery wastewater for leather processing can be achieved. The membrane fouling issues are being addressed in the treatment system as well as by introducing cleaner process technologies. In the present study, it is shown that incorporation of metal oxides in the membranes improves the challenges in membrane bioreactors, thus highlighting the sustainable treatment strategies for further applied research and field applications.

Keywords: Membrane Bioreactor, Tannery wastewater, Sustainability.

1. Introduction

Tannery industry is an ancient industry that transforms raw hides and skins into leather for manufacturing articles like shoes, bags, suitcases, etc. India is the second-largest producer of footwear and leather garments. The Tannery industry is known for its traditional employments generating industries in India, which contributes about 13% of world leather production. Thus, this industry plays an important role in the Indian economy and contributes more in the field of export earnings. In leather processing, oneton raw material is converted into 0.2 ton of leather products. From theses process, 60% of solid waste is

generated. However, the major drawback in the leather processing in tanneries are water intensive processes i.e., 28m3 of wastewater is generated from one ton of raw material processed, and these wastewaters is coming under the category of highly toxic and complex nature.

Alkalis, Acids, solvents, dyes, auxiliary chemicals, etc., in During leather processing various chemicals such as acids, alkalis, sulphides, Chromium salts, tannins etc., are used [2][3]. Chemical Oxygen Demand of tannery wastewater is estimated that for 1 tonnes of raw hide, it is bout 100– 120 kg [4], which is 55% of the COD in the global effluent. This high strength wastewater is treated by conventional treatment consisting of biological

processes like activated sludge process. This process requires a large footprint, high operating and maintenance costs. Also, the regulatory bodies pose more stringent norms to the tanneries to meet the environmental norms. In few places, due to water demand, regulatory bodies mandate the implementation of zero liquid discharge (ZLD). To achieve the ZLD system, the treatment plants have to set the Reverse Osmosis system in the addition to the conventional Activated Sludge Process (ASP). This addition became energy intensive due to the presence of TSS and turbidity in the feed water of RO system. To overcome the disadvantages of this system, development of economically and technically feasible unit became the need for the hour [5]. In such cases, membrane bioreactors (MBRs) can be an alternative as it requires small footprint, minimizes the wasting of sludge from the biological treatment unit and longer Sludge Retention Time (SRT) to achieve high quality permeate [6].

In last one decade, Membrane Bioreactors (MBRs) are a very promising technology for treatment of high strength wastewater like tannery wastewater, with the main benefit of achieving complete removal of suspended solids, exclusion of secondary clarifier, and producing high quality permeate that is suitable for reverse osmosis (RO) feed. Recent research works shows that a higher removal rate is achieved compared to the conventional activated sludge process for wastewater treatment [7].

MBRs typically removes COD removal up to 99 percent whereas ASP achieves 95 percent. However, so far, the large-scale MBRs are well-known for the municipal wastewater and polluted surface water treatment [8]. The capital cost of the ASP is higher but MBR requires a smaller tank which might reduce cost. But the cost of the membranes is high so it is important that pre-treatment may be necessary to reduce the chance of membrane damage, wastewater ought to go through an excessive stage of particle elimination previous to the MBR [9]. In general, MBR requires 1 to 3 mm fine screens to avoid the clogging issues before the membranes [10].

Though membrane bioreactor is pretty effective in addressing the industrial effluents, it has a disadvantage of biofouling which limits its large-scale application of MBR. In recent years, extensive research has been done to reduce the bio-fouling. During MBR operation, if notable sharp increase in TMP during constant flux operation is observed, then it indicates severe membrane fouling and this is called as TMP jump [11].

It was found that TMP jump from 5 kPa to 15 kPa within few days of operation at 20 LMH [12] indicating membrane fouling because of EPS released by the microbes. So, to improve the efficiency of MBR, antifouling membranes should be used and to improve the life of the membrane. The MBR permeate is free from turbidity and suspended solids, which can be best feed for RO treatment so that the reuse of treated tannery wastewater for leather processing will be achieved.

The objective of this study is to develop a submerged membrane bioreactor for tannery wastewater treatment by fabricating fine-tuned anti-fouling membranes. For that purpose, the COD removal efficiency and the fouling behavior of commercial PVDF hollow-fiber membranes were studied. Then with those results, a fine-tuned anti-fouling flat sheet membrane with and without the addition of TiO_2 has been prepared. The characterization of the same along with fouling behavior have been compared.

2. Materials & Methods

2.1 Reagents

Loba Chemicals Pvt Ltd, India supplied the NaOCl required for the ex-situ chemical cleaning of membranes. N-methyl-2-pyrrolidone (NMP) and PVDF powder used in the synthesis of membranes were purchased from Sisco Research Laboratories, India. PVP polymer, as a pore former and an additive in the synthesis of membrane were purchased from HiMedia Laboratories Pvt Ltd, India. Other chemicals used in the experiments were purchased from Sisco Research Laboratories, India. A commercial PVDF membrane with a pore size of 0.1µm was brought from Hollowbrane Membrane Technologies, Chennai. All chemicals used in this study were reagent grade.

Table 1. Characterization of Tannery Waste Water

PARAMETERS	TESTING METHODS	VALUES	
pH	Digital pH meter	7.9	7.6
COD (mg/L)	Closed Reflux Method	6080	3200
BOD (mg/L)	Winkler’s Iodometric Method	1560	720
TSS (mg/L)	Gravimetric Method	2670	895
TDS (mg/L)	Gravimetric Method	20670	8000

2.3 Membrane Specification

PVDF hollow fiber membrane with a pore size of 0.1µm and surface area of 0.65 m2 was used in the reactor. The complete specification of the membrane is given

Table 2. Membrane specifications

Parameters Characteristics

Pore size 0.1 µm

Maximum pressure 1 bar

Surface area 0.65 m

Membrane type PVDF

2.2 Characterization of Tannery Waste Water

The tannery wastewater was collected from the tannery common effluent treatment plant, Ranipet, and the common effluent treatment plant, Pallavaram. The samples were collected in a 25-litre plastic cans, which was transported and then stored in the laboratory. The characterization of which is then carried out and values are shown in Table.1. A digital pH meter was used to measure the pH of raw wastewater samples. COD was calculated by the closed reflux method and BOD was calculated by Winkler's Iodometric method. MLSS and total dissolved solids (TDS) were also determined based on standard methods for the examination of water and wastewater [13]. The measurements were done in triplicate throughout the analysis. The influent COD, permeate COD, and MLSS were measured on a daily basis.

VALUES

(RANIPET)

(Pallavaram)

in Table.2. The membrane was physically cleaned by backwashing with permeate water for a period of 5 minutes for every 2 hours. Chemical cleaning was done using sodium hypochlorite (0.5%) by soaking the membrane for an entire night.

2

2.4 Sludge Acclimatization

After the acclimatization process, the nutrients have been added to the increase the MLSS concentration in wastewater. In order to maintain the constant reactor volume, three-way controlled valve has been installed to recycle the part of permeate. In a week of time, the MLSS concentration began to increase and reached about 6000mg/L. The wastewater with higher MLSS concentration has been transferred to the reactor and the feed was sent to the reactor from a feed tank at a pre-set flow rate. In order to maintain the constant reactor volume, a three-way controlled valve has been installed to recycle the part of permeate. MLSS concentration was found to increase by a value of about 7000 mg/L. It may be noted that previous research indicated that COD value started decreasing once MLSS concentration reached 5000 mg/ L [14]. From this study also, it is observed that the COD value started decreasing as the MLSS concentration reached 5000 mg/L.

2.5 Fouling Measurements

The required operational parameters to be optimized are flux and TMP with COD, and TSS calculated at regular intervals. The membrane used here is a microfiltration membrane which was made of PVDF, the TMP of the membrane was operated at 1 bar. The variation of flux with respect to time is plotted as a graph and the optimum flux value is noted. The Flux of the membrane (J) was calculated using the following equation 1.

Q

A (1)

Flux(J) =

Where Q is the volume of permeate per hour; A is Surface area. Fouling may be classified as reversible and irreversible. Irreversible fouling (Rir) and Reversible fouling used as a measure to determine irreversible flux loss and reversible flux loss and it can be calculated by using

the following equations 2 and 3 [15] [14],

J w 1−Jw 2

Jw 2 (2)

Rir =

where Jw1 represents pure water flux and Jw2 represents pure water flux after physical and chemical cleaning

$$Rrev = \frac{Jw\,2 - Jp}{Jw\,1} \quad (3)$$

Where Jp is the flux with MBR filtration of wastewater. Jw1 represents pure water flux and Jw2 here stands for pure water flux after physical cleaning. To determine the extent of fouling, the percentage reduction in permeate flux (PRPF) can be used and calculated by the following equation 4 [15] [14],

$$PRPF(\%) = \frac{Ji - Jf}{Ji} \quad (4)$$

where Ji is the initial flux and Jf is the final permeate flux at the end of the experiment.

2.6 Synthesis of TiO2 Nano Particles

The synthesis of TiO2 nanoparticles as was done which is by first dissolving 5 ml of Titanium (IV) butoxide in 50 ml of Dimethyl Sulfoxide [16]. It is then heated at 190°C for 2 hours with continuous mechanical agitation. After this reaction, the precipitate was separated by centrifuging at 4000 rpm for 10 minutes multiple times after each run the precipitate was washed with ethanol/acetone in (2:1) ratio. It was then vacuum dried at 50°C for 12 hours to yield a dry white TiO2 powder. The white TiO2 powder was then calcined at 400°C to produce TiO2 nanoparticles.

2.7 Characterization of TiO2 Nano Particles

SEM analysis is done using SEM–EDAX (F E I Quanta FEG 200) to observe the surface morphology of the synthesized nanoparticles and EDX analysis was done to find out the presence of TiO2 nanoparticles [17]. XRD analysis was done to determine the crystallinity of TiO2 nanoparticles using PAN analytical XPERT PRO Diffractometer.

2.8 Synthesis of Fine-Tuned Membrane

The synthesis of fine-tuned membranes involves the usage of PVDF membranes with anti-biofouling material which we synthesized using TiO2 nanoparticles, N-Methyl-2-

Table 3.3 Composition of Flat Sheet Membranes

MEMBRANE	PVDF (wt %)	PVP (wt %)	TiO2 (wt %)	NMP (wt %)
SAMPLE 1 (S1)	16	3	0	81
SAMPLE 2 (S2)	15.52	3	0.48	81

pyrrolidone (NMP) as solvent, and PVP additive is used as a pore former. The preparation method involved is the same as that of the “phase inversion” method employed in earlier works by other researchers (17).

2.9 Characterization of Fine -Tuned Membrane

SEM analysis was carried out to find the influence of composition on the final membrane structure, and crosssections of the flat sheet membranes in the absence and presence of TiO2 nanoparticles using SEM–EDAX (F E I Quanta FEG 200). TGA analysis was carried out to determine the presence of TiO2 nanoparticles in the membrane and how much influence it has in increasing the thermal stability of the membranes. It is carried out at a heating rate of 10°C/min from 50°C to 800°C under a nitrogen atmosphere. The FTIR spectra of the membranes were measured using an FTIR-ATR spectrometer operating in the wave number range of 4000– 400 cm-1.

2.10 Reactor Experimental Work

The membrane filtration reactor is having a working volume of 15L. The filtration experiments were carried out by using MBR test skid. (Fig.2). The commercial

Fig.1 Experimental set-up of Submerged MBR and Photograph showing fabricated MBR

and fine-tuned antifouling membranes were used to perform the filtration experiments with a membrane surface area of 0.6m2. The Trans membrane pressure (TMP) in the experiments were maintained about 100kPa. The membranes were submerged into the reactor containing tannery wastewater. Stone diffusers for fine aeration, were placed at the lower part of the tank. The MLSS concentration in the reactor was maintained upto 9000 mg/L in the reactor. The membranes were cleaned periodically by providing backwash and the pure water flux was determined for each run. After the filtration, the flux values were determined to know about the extent of fouling. The permeate was taken for analysis to study the pollutant removal.

3. Results & Discussion

3.1 Permeate Flux

The reactor was operated at an HRT of 8 h and the aeration was given without any interruption. The permeate flow was around 9 L/h which implies a flux value of 13.85 LMH when operated at a constant TMP of 1 bar. During its entire operation in the first week, the flux value was around 13 to 13.85 LMH. On day 7 the flux value dropped below 13 LMH and backwashing has been given for 5 mins. After the backwashing, the flux was restored to 12 LMH. After the 7th day of the experiment, backwashing was given at regular intervals for every 2hrs of operations. The MLSS concentration from day 11 to day 14 remained at 7600 mg/l. So, the aeration provided has been increased

Fig 3.1 (a) Value of COD w.r.t MLSS, (b) Permeate Flux Value

3.2 Fouling Measurements

To determine the type of fouling that has caused the major impact, reversible and irreversible fouling calculations have been done. Loose deposition solids on the surface of the membrane cause reversible fouling which can be removed by backwashing. In the case of commercial PVDF membrane irreversible fouling (64.6 %) tends to dominate more than reversible fouling (7.6%). This implies that the contaminants are strongly attached to the surface of the membrane causing pore blockages which cause irreversible fouling. The percentage reduction in flux in the case of commercial PVDF membrane employed MBR

along with the addition of external nutrients and the reactor is given rest for a day while keeping the aeration on. On day 15 we could see a slight increase in MLSS concentration and the COD removal was also increased to 80%. After the 10th day even with backwashing the flux kept decreasing reaching 3.23 LMH on the 26th day as shown in the Fig 3.1 indicating the need for chemical cleaning. The average flux during this run was found to be 8.4 LMH. The flux value dropped below 3.5 LMH for three consecutive days even after backwashing. Then the membrane was chemically cleaned by immersing them in 0.5% NaOCl solution for the entire night. After chemical cleaning the flux increased to 7.08 LMH achieving 50% recovery. During the entire operation, the value of COD w.r.t MLSS concentration was noted as shown in Fig 3.1.

is 77 %. The irreversible fouling was found to be 64.6% and the reversible fouling was found to be 7.6%. PRPF (%) was calculated and found to be 77%.

3.3 Removal of Permeate Colour

The colour of the permeate collected from the reactor was not satisfactory as it was not removed completely. Though there are no suspended solids present, it is coloured this could be due to the addition of dyeing agents during leather processing. The absorbance value of the raw sample was analyzed for different wavelengths and a spectrum was drawn. The maximum absorbance value

of raw wastewater (10.00) and permeate (5.312) was noted at 265 nm. After the MBR treatment process, the maximum colour removal was found tob 57%.

3.3.1 Ozonation

Ozonation has been given for colour removal of the permeate with an ozone concentration of 4 g/h. Ozonation involves the production of ozone gas which is naturally

A B C

Fig 3.3 (A) Raw wastewater, (B) Permeate collected from MBR, (C) After ozonation

3.4 Characterization of TiO2 Nano Particles

The SEM and EDX spectrum of TiO2 nanoparticles are shown in Figure 3.4 The EDX spectrum of TiO2 nanoparticles indicates high purity as only Ti and O elements can be detected. The SEM images shows that

Fig 3.4 SEM images of the synthesized TiO2 nanoparticles (A) at 2µm (B) at 1 µm (C) at 500nm (left) and

SEM-EDX analysis of TiO2 nanoparticle (right)

available and also ozonation does not impart any chemicals to the water. Ozonation have been given for a period of 90 mins and the sample was collected at 30 mins intervals. The absorbance value of the same is also noted at 265 nm. Thus after ozonation, the colour removal was achieved up to 93% during pre-ozonation of MBR system i.e., ozonation in feed water. Whereas, 83% colour removal has been observed with post-ozonation of MBR system i.e., ozonation with the permeate.

synthesized nanoparticles is a spherical shaped structure. The average particle size of TiO2 nanopaticles was in the

range of 30-40 nm which was similar to the average particle size found using XRD analysis. The XRD pattern

of TiO2 nanoparticles are shown in Fig 3.5.

Fig 3.5 X-Ray Diffraction of TiO2 Nanoparticles

It clearly indicates well crystallized and pure TiO2 nanoparticles. The Peak broadening observed on XRD clearly indicates small particles size (16). Peaks were absorbed at 25°, 38°, 48°, 55°, 62° and 75p along with miller indices values (1 0 1), (1 1 2), (2 0 0), (2 1 1), (2 1 3) and (2 1 5) respectively.

$D = K. \lambda \beta. COS\theta$

(5)

Fig 3.6 FTIR Spectra of neat PVDF and PVDF/TiO2 membranes

3.6 SEM Analysis of PVDF/TiO2 Membranes

The SEM image of PVDF/TiO2 membranes has been shown in Figure 3.7. From the image, it can be clearly seen that the TiO2 nanoparticles have been uniformly coated on the surface of the membranes. With antifouling properties of TiO2 this uniform coating will

The average size of the crystallites, estimated from the FWHM of the TiO2 (101) diffraction peak using Debye-Scherrer’s relation, was of the order of 29.72nm for the TiO2 NPs.

3.5 Characterization of Fine-Tuned Membranes

3.5.1 FTIR Analysis

The FTIR spectra of neat PVDF and PVDF/TiO2 membranes in the range 500-4000 cm-1 are shown in Figure 3.6 above. The peaks observed in 613.37 cm-1, 761.79 cm-1, 795.93 cm-1 could be due to the α-phase PVDF crystals [18]. The peaks observed in 1105 cm-1, 1240 cm-1 were due to CF2 groups of PVDF polymeric phase [19]. The peaks observed in 1670 cm-1 is due to the carbonyl group of PVP [20]. The peaks observed in 3440 cm-1 was due to the O-H groups. Furthermore, there is no additional peaks due to the addition of TiO2 into the membranes indicating TiO2 interacted only physically with the PVDF membranes.

ensure the resistance to membrane fouling. It can also be seen that the addition of TiO2 have produced larger pores on the surface of the membrane. The usage of TiO2 nanoparticles at 0.5% has ensured that there is no agglomeration of the nanoparticle as TiO2 with more than 1% have produced large nanofillers resulting in pore blockage and decrease in water flux [21].

Fig 3.7 SEM Images of PVDF/TiO2 membranes at (A) 224 µm, (B) 75 µm, (C) 27 µm.

TGA Analysis of PVDF/TiO2 Membranes

Initial degradation of neat PVDF membranes happened

at 320°C the addition of TiO2 delayed the degradation of

PVDF/TiO2 membrane to 365°C. This clearly shows that

the addition of TiO_2 has enhanced the thermal stability of

the membrane. At the end of the degradation curve at

790°C the residual weight of the neat PVDF membrane

(38%) was less than the PVDF/TiO_2 membrane (48%).

Thus, the presence of TiO_2 has delayed the decomposition

of the PVDF/TiO_2 membrane.

Flux Measurements

The fouling behaviour of the fine-tuned membranes have been observed. For this purpose, a similar reactor setup has been used. The pure water flux of the fine-tuned PVDF membrane was 15 LMH. The flow of PVDF/TiO_2 membrane was 9.5 L/h and the area was the same as mentioned above. There was no flux decline for continuous operation of 10 days and this also shows that the addition of TiO_2 has increased the hydrophilicity and porosity of the membrane. It is also said that most polymer membrane with good hydrophilic characteristics have shown good fouling resistance [22]. The permeate flux of neat PVDF membrane and PVDF/TiO_2 membrane was found to be 13 LMH and 15 LMH. The drop in permeate flux of neat PVDF membrane observed after 3 days whereas there was no decline in the permeate flux of PVDF/TiO_2.

4. Conclusion

The commercial PVDF membranes have shown an average flux value of around 9 LMH and COD removal efficiency of upto 89% have been achieved. Even though chemical cleaning with NaOCl (0.5%) have resulted in 50% flux recovery, the flux again dropped just after 4

days of operation indicating the irreversible fouling being dominant. On comparing, the nanoparticle-coated PVDF/ TiO_2 flat sheet membranes have shown better characteristics in fouling resistance than the neat PVDF membranes because of their anti-fouling properties. The addition of TiO_2 being able to produce larger pores than the neat PVDF membranes have resulted in increasing the hydrophilicity of the membrane which is indicated by higher pure water flux and permeate flux of PVDF/TiO_2 membranes. With these results further study can be done by incorporating the same composition of TiO_2 and PVDF in preparing the PVDF/TiO_2 hollow fibre membranes.

Reference

1. Sivaram, N.M. (2019). Energy from Toxic Organic

Waste for Heat and Power Generation || Toxic Waste From Leather Industries., (), 55– 67. doi:10.1016/B978-0-08-102528-4.00005-5.

2. Lofrano G, S. Meric¸, G.E. Zengin, D. Orhon

(2013), Chemical and biological treatment technologies for leather tannery chemicals and wastewaters: a review, Science of Total Environment. 461–462 265–281

3. Durai G, M. Rajasimman, (2011), Biological

treatment of tannery wastewater – a review, Journal of Environmental Science. 4, 1–17

4. J.A. Mendoza-Roca; M.V. Galiana-Aleixandre;

J. Lora-García; A. Bes-Piá (2010). Purification of tannery effluents by ultrafiltration in view of permeate reuse. , 70(3), 296–301. doi:10.1016/ j.seppur.2009.10.010 Chung, Han-Na Choi, SangEun Lee, and Jong-Bok Cho, (2004). Treatment of Tannery Wastewater with High Nitrogen Content Using Anoxic/Oxic Membrane Bio-reactor (MBR), Journal of Environmental Science and Health, Vol. A39, No. 7, pp. 1881–1890.

5. Keerthi; V. Suganthi; M. Mahalakshmi; N.

Balasubramanian (2013). Development of hybrid

membrane bioreactor for tannery effluent treatment., 309(none), –. doi:10.1016/ j.desal.2012.10.014

6. Mannucci A, G. Munz, G. Mori, C. Lubello (2010),

Anaerobic treatment of vegetable tannery wastewaters: a review, Desalination 264 1– 8.

7. Qin L, Y. Zhang, Z. Xu, G. Zhang (2018),

Advanced membrane bioreactors systems:new materials and hybrid process design, Bioresource Technology. 269 476–488.

8. Wastewater Management. Membrane Bioreactors [Fact sheet]. U.S. Environmental Protection Agency. Membrane Bioreactors factsheet (epa.gov)

9. Wallis-Lage, C., B. Hemken, et al. 2006. MBR

Plants: Larger and More Complicated. Presented at the Water Reuse Association's 21st Annual Water Reuse Symposium, Hollywood, CA, September 2006.

10. Zhang J., Chua H.C., Zhou J., Fane A.G (2006).

Factors affecting the membrane performance in submerged membrane bioreactors. Journal of Membrane Science, 84: 54–66. doi: 10.1016/ j.memsci.2006.06.022.

11. Yung Jo, (2019). A comparative study on nitric

oxide and hypochlorite as membrane cleaning agent to minimize biofilm growth in a membrane bioreactor process, Biochemical Engineering Journal, 148, 9-15

12. APHA (2005), Standard methods for the

examination of water and wastewater, 21st edition. American Public Health Association, Washington, DC.

13. Sathya U, Keerthia, M. Nithyaa, N.Balasubramanian, (2019). Evaluation of advanced oxidation processes (AOPs) integrated

membrane bioreactor (MBR) for the real textile wastewater treatment, Journal of Environmental Management, 246,768–775

14. Rajesh, S., Jayalakshmi, A., Senthilkumar, S.,

Sankar, H.H., Mohan, D.R., (2011). Performance evaluation of poly (amide-imide) incorporated cellulose acetate ultrafiltration membranes in the separation of proteins and its fouling propensity by AFM imaging. Industrial and Engineering Chemistry Research. 50, 14016–14029

15. A. Mezni, N. Ben Saber, M. Ibrahim, M. El-

Kemary, T. Altalhi and L. S. Smiri, (2017), Facile Synthesis of High Thermally Stable TiO2 Photocatalyst, New Journal of Chemistry. DOI: 10.1039/C7NJ00747G.

16. Li, Tingting, Yong Gao, Junwo Zhou, Manying

Zhang, Xiaofei Fu, and Fang Liu. 2019. "A Membrane Modified with Nitrogen-Doped TiO2/ Graphene Oxide for Improved Photocatalytic Performance" Applied Sciences 9, no. 5: 855. https://doi.org/10.3390/app9050855

17. Abba, Mohammed Umar, Hasfalina Che Man,

Raba'ah Syahidah Azis, Aida Isma Idris, Muhammad Hazwan Hamzah, Khairul Faezah Yunos, and Kamil Kayode Katibi. 2021. "Novel PVDF-PVP Hollow Fiber Membrane Augmented with TiO2 Nanoparticles: Preparation, Characterization and Application for Copper Removal from Leachate" Nanomaterials 11, no.2: 399. https://doi.org/10.3390/nano11020399

18. Fengmei Shi; Yuxin Ma; Jun Ma; Panpan Wang;

Weixiao Sun (2012). Preparation and characterization of PVDF/TiO2 hybrid membranes with different dosage of nano-TiO2, 389(none), 522–531. doi:10.1016/j.memsci. 2011.11.022

19. Kamaludin, Roziana, Lubna Abdul Majid, Mohd

Hafiz Dzarfan Othman, Sumarni Mansur, Siti Hamimah Sheikh Abdul Kadir, Keng Yinn Wong, Watsa Khongnakorn, and Mohd Hafiz Puteh. 2022. "Polyvinylidene Difluoride (PVDF) Hollow Fiber Membrane Incorporated with Antibacterial and Anti-Fouling by Zinc Oxide for Water and Wastewater Treatment" Membranes 12, no. 2: 110. https://doi.org/10.3390/membranes12020110

20. Rusli, Ummi Nadiah; Alias, Nur Hashimah;

Shahruddin, Munawar Zaman; Othman, Nur Hidayati; Alsultani, K.F.; Eguchi, K.; Heeres, H.J.; Al-Baidhani, J.H.; Su, Y.; Al-Zuhair, S.; Yang, S.-T.; Chen, Y.-S. (2016). Photocatalytic Degradation of Oil using Polyvinylidene Fluoride/ Titanium Dioxide Composite Membrane for Oily Wastewater Treatment. MATEC Web of Conferences, 69(), 05003–. doi:10.1051/ matecconf/20166905003

21. Méricq, J.-P.; Mendret, J.; Brosillon, S.; Faur, C.

(2015). High performance PVDF-TiO2 membranes for water treatment. Chemical Engineering Science, 123(), 283– 291. doi:10.1016/j.ces.2014.10.047

22. Liu, Q.; Huang, S.; Zhang, Y.; Zhao, S. (2018).

Comparing the antifouling effects of activated carbon and TiO2 in ultrafiltration membrane development. J. Colloid Interface Sci. 515, 109–118.

23. Aravind, M., Amalanathan, M. & Mary, M.S.M

(2021). Synthesis of TiO2 nanoparticles by chemical and green synthesis methods and their multifaceted properties. SN Appl. Sci. 3, 409. https://doi.org/10.1007/s42452-021-04281-5

24. Abd Mutalib, M. (2017). Membrane Characterization || Scanning Electron Microscopy (SEM) and Energy-Dispersive X-Ray (EDX) Spectroscopy. , (), 161–179. doi:10.1016/B9780-444-63776-5.00009-7