Energy effiient harvesting of Spirulina sp. from the growth medium using a tilted panel membrane fitration

by Insyirah Ismail

1

Bioresource Technology Reports 15 (2021) 100697

Contents lists available at ScienceDirect

Bioresource Technology Reports

journal homepage: www.sciencedirect.com/journal/bioresource-technology-reports

Energy efficient harvesting of *Spirulina* sp. from the growth medium using a tilted panel membrane filtration

Insyirah Ismail[a], Kiki Adi Kurnia[b], Shafirah Samsuri[a], Muhammad Roil Bilad[a,c,*], Lisendra Marbelia[d], Noor Maizura Ismail[e], Asim Laeeq Khan[f], Arief Budiman[b], Susilawati Susilawati[g]

[a] Department of Chemical Engineering, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak, Malaysia
[b] Department of Marine, Faculty of Fisheries and Marine, Universitas Airlangga, Jalan Mulyorejo Kampus C, Surabaya 60115, Indonesia
[c] Department of Chemistry Education, Universitas Pendidikan Mandalika (UNDIKMA), Jl. Pemuda No. 59A, Mataram 83126, Indonesia
[d] Department of Chemical Engineering, Faculty of Engineering, Universitas Gadjah Mada, Jl. Grafika No. 2, Yogyakarta 55281, Indonesia
[e] Faculty of Engineering, Universiti Malaysia Sabah, Jln UMS, Kota Kinabalu 88400, Sabah, Malaysia
[f] Department of Chemical Engineering, COMSATS University Islamabad, Islamabad, Pakistan
[g] Master of Science Education Program, University of Mataram, Jl. Majapahit No. 62, Mataram 83125, Indonesia

ARTICLE INFO

Keywords:
Tilted panel system
Membrane fouling
Microalgae filtration
Spirulina sp.
Nutritional food source

ABSTRACT

Membrane fouling is one of the main drawbacks in membrane-based microalgae harvesting. This study assessed the tilted panel to enhance filtration performance of *Spirulina* sp. broth. The influences of the operating parameters including the tilting angle, aeration rate and membrane materials on filtration performance and energy consumption were evaluated. Results showed that the system was effective and energy-efficient for membrane fouling control. The permeability peaked at a tilting of 45° thanks to combination of aeration and panel tilting. The microfiltration performed better than the ultrafiltration membrane due to the effective impact of air bubbles for foulant scouring that maximized the membrane intrinsic property. Small aeration rate of 1.0 L/min offered a high plateau permeability of 540 L/(m^2·hr·bar) in which reversible fouling almost fully absent. The high permeability could be achieved under a low energy input of 0.2 kWh/m^3.

1. Introduction

Spirulina sp.-based bioproducts are rich in bioactive compounds such as protein, vitamins, beta-carotene, and minerals which make it suitable to be utilized extensively in food and beverage productions as well as pharmaceuticals (Silva et al., 2019). Nature derivative products produced through green processing are also more preferred by consumers (Tang et al., 2020). Chemically synthesized products often contain a minor fraction of by-products that impose long-term health issues such as hyperactivity, cancer development, and allergic reaction (Vaz et al., 2016). The sulfated polysaccharide in *Spirulina* sp. is commercialized into tablets, pills for food supplements as it can prevent infection from numerous viruses (HIV-1, herpes virus and cytomegalovirus) and can delay the growth of cancerous cells (Andrade, 2018). These compounds are safe for direct consumption to humans and harmless to the environment.

In spite of its vast potentials, microalgae are known to have a density similar to water and the cell possesses small size which complicates the harvesting process (Bilad et al., 2014a). The *Spirulina* sp. biomass must be harvested prior to further processing. The available options for biomass harvesting methods include coagulation/flocculation, centrifugation as well as membrane filtration. The centrifugation method is energy intensive. On the contrary, membrane filtration is low in energy foot-print and usage of chemicals, offers almost full biomass recovery, and is increasingly more cost-effective (Ríos et al., 2012). Thus, the purity of biomass is guaranteed unlike the excess ions from coagulant and flocculant in the coagulation/flocculation process (Bilad et al., 2012). This way, application of membrane technology for *Spirulina* sp. biomass can enhance the economic feasibility of *Spirulina* sp.-based products.

However, membrane fouling strictly limits filtration of a microalgae broth (Bilad et al., 2012). The severity of fouling varies between micro- and ultra-filtration membranes due to the difference in mass-transfer resistance (Lau et al., 2020). Several types of fouling such as cake

* Corresponding author at: Department of Chemistry Education, Universitas Pendidikan Mandalika (UNDIKMA), Jl. Pemuda No. 59A, Mataram 83126, Indonesia.
E-mail address: muhammadroilbilad@ikipmataram.ac.id (M.R. Bilad).

https://doi.org/10.1016/j.biteb.2021.100697
Received 20 January 2021; Received in revised form 29 March 2021; Accepted 30 March 2021
Available online 16 April 2021
2589-014X/

layer formation, pore blocking and internal fouling could occur during microalgae harvesting process (Bilad et al., 2014a). The cake layer is the major culprit of membrane fouling, which contributes up to 80% of the filtration resistance (Lee et al., 2001). Therefore, many studies have tried to address the cake layer fouling issue. They include enhancing the operational conditions, conducting cleaning cycles, applying dynamic membrane filtration (DMF) system and air bubbling system (by inducing shear rates) (Eliseus et al., 2017). The cleaning cycles comprise of physical and chemical cleanings, but the latter is known to shorten the membrane lifespan. Besides, the DMF system applied by either vibrating or rotating the membrane poses challenge of high complexity for scaling up (Bilad et al., 2014a).

Air bubbling is one of the proven methods to manage cake layer fouling (Eliseus et al., 2017). In the air bubbling system, the foulant is scoured-off by the air bubbles without damaging the membrane (Hwang et al., 2015). The hydrodynamic forces exerted by the air bubbles onto the membrane surface help to limit the concentration polarization, which in turn reduces the fouling rate (Tian et al., 2010).

Despite of the aforementioned advantages, the conventional air bubbling system in the typical vertically aligned plate-and-frame module has few limitations (Eliseus et al., 2017; Hwang et al., 2015). In the vertical panel, the contact of air bubbles towards the membrane surface is low since the bubbles travel in the center of the two adjacent panels, not on the membrane surface (Eliseus et al., 2017). On the other hand, the horizontal panel requires a large footprint due to difficulties in large-scale module alignment which led (Eliseus et al., 2017) to introduce a tilted panel system. For the inclined tubular membrane, the membrane permeability increases by inclining the module up to 45° in an organic tubular membrane module, beyond which it declines (Cheng, 2002). Meanwhile, a pioneer study using polyvinylidene difluoride (PVDF) membrane in a tilted panel was only done for the tilting angle of up to 20° because at that angle the permeability already reaches the plateau value (Eliseus et al., 2017). So far, no study was conducted on the effect of permeability for the tilted panel system beyond tilting angle of 20° despite a model showed the optimum performance at tilting angle of 45° and no report available on the application for such system for *Spirulina* sp. feeds. In addition, the study on *Spirulina* sp. feeds using different membrane materials is still lacking; it is best to extend the tilting angle since to identify the optimum value experimentally.

This study evaluates the filtration performance of PVDF and polysulfone (PSF) membranes in a tilted panel system, evaluated at 0, 20, 45 and 70° of tilting angles for harvesting *Spirulina* sp. The permeability enhancement was assessed under several operating parameters, namely aeration rate and *Spirulina* sp. biomass concentration. Lastly, the energy estimation and comparison with other studies were also systematically discussed.

2. Materials and methods

2.1. Preparation and characterization of membrane

The PVDF and PSF membranes were prepared in house by using the phase inversion method with the addition of 1% (w/w) polyethylene glycol (PEG, 20 kDa, Sigma-Aldrich). The dimethylacetamide (DMAC, Sigma-Aldrich) as the solvent was mixed with the polymer at concentration of 15% to form a polymer solution. The bubble-free and homogeneous polymer solution was hand casted at average speed of 2 cm/s at room temperature of 24 °C and air humidity of 70% on a non-woven fabric (Novatexx 24413, Freudenberg-filter, Germany) to avoid shrinkage, followed by immersion in a bath containing water (acting as the nonsolvent) at temperature of 24 °C. The membrane sheet was formed in the coagulation bath, in which the completion of the phase inversion was identified as the point when the sheet floated from the plate. The resulting membrane was then washed using running tap water for 5 min to remove the residual solvent and the membrane was stored wet in water until further use. The effective membrane area for each panel was 0.014 m^2 (10 cm × 14 cm). The PVDF and PSF based membranes were selected because they are mostly reported in literature for microalgae harvesting. The former represents the microfiltration type, while the latter represents the ultrafiltration type.

The morphology of each membrane was analyzed by using scanning electron microscopy (SEM, ZEISS). The electron digital micrometer screw gauge was used to measure the thickness of the membrane, whereas the capillary flow porometer (Porolux) was used to determine the pore size and distribution. The contact angle of the membrane surface was measured by using the sessile drop method with a drop size of 1 μL.

2.2. Microalgae broth preparation

The inoculum of *Spirulina* sp. was collected from a full-scale open pond system, then cultivated in a 15-L reactor using Walne's medium (Azma et al., 2011). The pH value of the medium was adjusted to 8. Aeration at a rate of 1.5 L/min was provided as the source of inorganic carbon, while the light as source of energy was provided from 18 Watt Neon lamp continuously. The microalgae broth reached the stationary growth phase after 10 days of cultivation, obtaining biomass concentration of approximately 1.2 g/L. All the filtration tests used the same feed concentration, except for the one for evaluating the impact of *Spirulina* sp. biomass concentrations (2.2–2.5 g/L). The same microalgae broth could be used for evaluation of one parameter (i.e., effect of tilting angle) as *Spirulina* sp. has a long stationary phase for about 6 days (de Jesus et al., 2018). Another cultivation was done for evaluating the impact of other parameters.

2.3. Experimental set-up

The filtration performance of microalgae was investigated in a constant-pressure mode using a tilted panel system illustrated in Fig. 1. The air pump was used to supply air bubbles from underneath the membrane panel through a diffuser, as such the air bubbles scour-off the foulant during the filtration. The aeration rate was set constant and was provided continuously without idle phase in the range of 0.5–1.5 L/min (depending on the testes parameter). A vacuum air pump was utilized to create a constant vacuum pressure of 0.1 bar. The filtration was done in 9/1 min cycles of filtration and relaxation. During the relaxation period, the air pump was switched off but the membrane aeration was maintained. The volume of permeate was measured during the relaxation period by using a measuring cylinder. After volume measurement, the permeate was returned into the feed tank to ensure a constant level and condition of the feed.

2.4. Filtration test

The filtration tests were conducted by using the PVDF and PSF membranes to investigate the effect of membrane properties, tilting angle, aeration rate and microalgae biomass concentrations towards the membrane permeability, as well as to compare the filtration performance of both membranes.

To evaluate the filtration performance, the flux (J, L/m^2·h) during filtration was calculated by using Eq. (1), whereas the permeability (L, L/m^2·h·bar) of the membrane was determined by using Eq. (2). In all filtrations, a complete rejection of biomass was achieved because of huge difference in the cell size (40 μm) and the membranes pore sizes (0.04 and 0.42 μm) and thus the rejection is not discussed in detail in the present study. All filtration tests were done at least in duplicate and are presented as mean±standard deviation to ensure the reproducibility of the data.

$$J = \frac{V}{At} \quad (1)$$

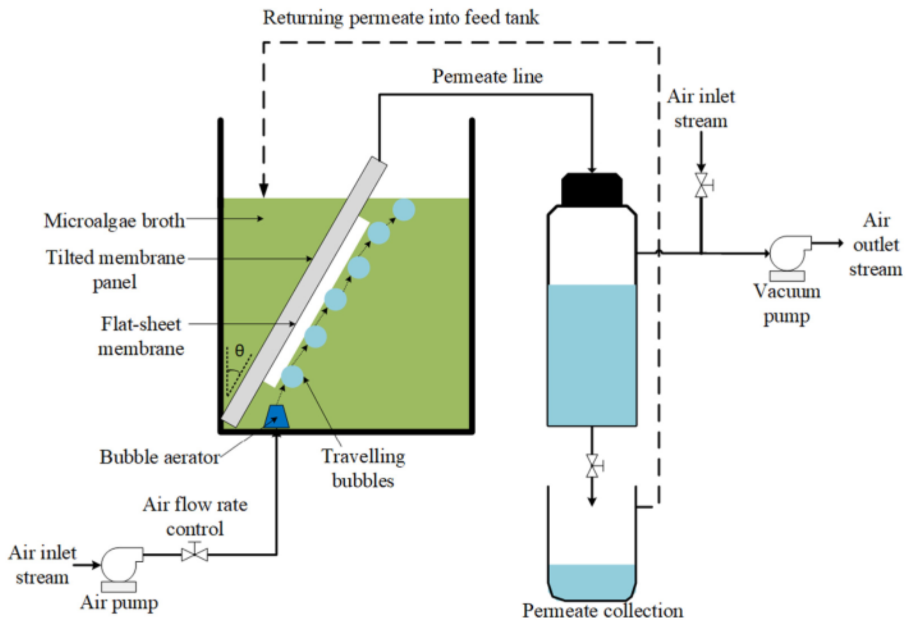

Fig. 1. Illustration of the lab-scale tilted membrane filtration system.

$$L = \frac{J}{\Delta P} \tag{2}$$

where V is the volume of permeate collected (L), t the duration of filtration (hr), A the effective area of filtration (m^2) and ΔP the trans-membrane pressure (bar).

The experiments to assess the effect of tilting angles were conducted at four tilting angles: 0 (vertical), 20, 45 and 70° for both the PVDF and the PSF membranes. The panel was tilted to the assigned angle, and it was hold using a holder to keep it intact. After placed according to the intended inclination angle, no change of angle was observed during the whole filtration tests. The filtration parameters when evaluating each tilting angle were kept constant at 1.0 L/min aeration rate, 7 L of feed volume and filtration cycle of 9 min on/1 min off.

Prior to the microalgae filtration test, the clean water permeability tests were conducted for 30 min. Afterwards, the microalgae filtration was carried out for 1 h until it reached its about constant permeability values. The permeate volume was measured during the 1 min of relaxation and used to calculate the permeability, resulting in a total of six permeability values in 1-hour of filtration test. Then, the membrane panel was rinsed with tap water and soaked into 1% of sodium hypochlorite for 1 h to restore its permeability value prior to the next filtration test. The results from the tilting angle study were used to select the membrane for further tests.

The filtration tests to evaluate the influence of aeration rate were run at aeration rates of 0.5, 1.0, 1.2 and 1.5 L/min using the PVDF membrane under a constant tilting angle of 45°. The performance was compared only at the tilting angle of 45° because it was found to be the optimum angle from the previous tests. Likewise, each filtration test was carried out for 1 h.

The study on the effect of feed concentration was done using broth with biomass concentrations of 2.15, 2.43, 2.51 and 2.55 g/L. During this tests, the aeration rate and the tilting angle was kept constant at 1.0 L/min and 45°, respectively. The microalgae broth solutions of 2.15, 2.43, 2.51, and 2.55 g/L were obtained by pre-concentrating the microalgae by filtration using another spare PVDF membrane to reach the desired concentration levels.

2.5. Energy estimation

Two different methods were applied to estimate the energy consumption for the filtration in a projected full-scale set-up. The first method utilized the full-scale data from a submerged membrane bioreactor (MBR) operation (Fenu et al., 2010). It was assumed that some equivalent parameters had similar energy consumption. The referenced parameters such as influent pumping (P^*_{IN}), permeate pumping (P^*_P), coarse bubble aeration (AER), cleaning in place (CIP) and air compression (AIR) were 0.03, 0.07, 0.23, 0.04 and 0.02 kWh/m^3, respectively. Nonetheless, the applied ΔP from the reference was 0.4 bar whereas in this current study was set at 0.1 bar. Therefore, the permeate pumping (P^*_P) was redefined accordingly (Osman et al., 2020). The energy consumption of the filtration was calculated by using Eq. (3) and was further simplified into Eq. (4).

$$E = P^*_{IN} + \frac{\Delta P}{\Delta P^*} P^*_P + \frac{J^*}{J}\left(AER^* + CIP^* + AIR^*\right) \tag{3}$$

$$E = 0.048 + \frac{8.12}{J} \tag{4}$$

where E is the estimated energy consumption (kWh/m^3), J^* flux obtained from the referenced study (28 L/($m^2 \cdot$ hr)) and J the flux obtained from this experiment (54.4 L/($m^2 \cdot$ hr)).

The second method only projected the aeration energy, according to the method reported elsewhere (Verrecht et al., 2008). To allow full-scale projection, a hypothetical full-scale module assembly was developed. It was assumed that the plate-and-frame module had a dimension of 50 × 100 cm, arranged in double-deck at panel gap of 0.5 cm. Thus, a flow channel of $A_x = 2.5 \times 10^{-3}$ m^2 existed in between the two panels, where feed liquid and air bubbles flow. Due to this configuration, the bubbles could flow over the membrane area of $A = 1.0$ m^2 along the flow channel. The aeration rate of 1.0 L/min through 10 cm width was translated to 5.0 L/min in the large-scale panel, corresponding to the aeration rate along the channel of $U = 8.3 \times 10^{-5} m^3/s$ or $U = 0.033$ m/s. The referenced parameters including the pressure (P), temperature (T), blower efficiency (ξ) and the distance of aerator nozzle from the surface (y), aerator constant (λ) were assumed to be 20 kPa, 298 K, 0.8, 2 m and ~1.4, respectively. Then, the aeration energy consumption was calculated by using Eq. (5).

$$E_A = \frac{PT\lambda}{2.73 \times 10^5 \xi(\lambda - 1)} \frac{UA_x}{JA} \left[\frac{10^4 y + P^{\left(1-\frac{1}{\lambda}\right)}}{P} - 1 \right] \tag{5}$$

where E_A is the estimated aeration energy (kWh/m^3) and J is the flux obtained from this study (54.4 L/($m^2 \cdot$ hr)).

2.6. Statistical analysis

The results on the assessment filtration parameters (membrane, tilting angle, aeration rate and concentration) were analyzed statistically. The significance of overall permeability in each parameter was evaluated using one-way analysis of variance (ANOVA) at 95% confidence intervals ($p < 0.05$). Then, the Tukey HSD post hoc was performed to identify which pairs of mean were significantly different. To allow statistical analysis, each filtration test was conducted twice.

3. Results and discussion

3.1. Membrane characteristics

The summary of PVDF and PSF membranes properties are provided in Table 1. Both membranes were asymmetric, typical of the ones produced using the phase inversion process (Tan and Rodrigue, 2019). The PVDF was microfiltration type and the PSF was ultrafiltration type, as such the impact of pore size on the filtration performance could be clearly compared. Microalgae suspension consisted of algae cells and algogenic organic matters (AOM: polysaccharides, protein etc.) (Zhang and Fu, 2018). The cell size of *Spirulina* sp. was approximately 40μm, much larger than the pore size of the PVDF and PSF the membranes. Theoretically, judging from the pore size of the membranes, the microalgae *Spirulina* sp. could be fully retained. However, some of the AOM smaller than the membrane pore size contained in the culture medium could still pass the membrane pores.

Apart from retaining the microalgal cells, it was also attractive to recover extracellular polysaccharides (EPS, a part of AOM) from the microalgae suspension due to its benefits as the food supplements or its richness in therapeutic compounds. The sulfated polysaccharides were considered as antiviral agent because it could inhibit the growth of viruses (Vaz et al., 2016). *Spirulina* sp. was well known for its capability in secreting abundant amount of AOM (Zhang and Fu, 2018). It was reported that the pilot scale of hybrid microfiltration and ultrafiltration could recover AOM from the culture medium (Li et al., 2011). The microfiltration was used to remove solid residuals and the AOM was then recovered from the microfiltration permeate using the ultrafiltration.

3.2. Comparison of PVDF and PSF membranes performance

Fig. 2 compares the hydraulic performance of the PVDF and PSF membranes in the tilted panel system operated under variable tilting angles. For the PSF membrane, the tilting angle of 45° showed the highest steady state permeability of 132.5, followed by tilting angles of 70, 20 and 0° of 123.4, 108.9 and 107.1 L/(m^2·h·bar), respectively. This trend was similar to the PVDF membrane that had the highest permeability of 377.4 at tilting angle of 45, followed by tilting angles of 70, 20 and 0° of 344.8, 312.1 and 282.2 L/(m^2·h·bar), respectively. The filtration performance of both membranes increased by tilting the panel up to the tilting angle of 45°, then dropped at the tilting angle of 70°. It is worth noting that the permeability values at 60 min of filtration were considered as quasi steady state value, in which prolonging the filtration would only slightly affect the permeability because of the low rate of membrane fouling. Nevertheless, as the occurrence of membrane fouling was inevitable, a slow decline in permeability was still expected over prolonged filtration time. However, the short-term filtration duration performed in this study was considered sufficient for comparative purpose. Fig. 2a shows the variation of permeability as function of time for PVDF membrane showing the same pattern with the PSF membrane (data not shown).

When comparing the PDVF and the PSF membranes, the one-way ANOVA analysis on the data on the impact of tilting angle obtained the p-values of 0.003 and 0.025, respectively. Those p-values were lower than the significance level of 0.05, indicating that the effect of the tilted panel configurations varied significantly. In this analysis, the means of the permeability values under all tested tilting angles for the two membranes were compared. Further analysis on the effect of tilting angle for the four data points using the Tukey HSD Test resulted in both membranes had Q-critical of 5.76. The PSF membrane had lower Q-statistic as compared to Q-critical for data at 0° vs 20° and 45° vs 70° which implied that the impact of tilting angle was only significant at a range of 20° to 45°. As for the PVDF membrane, the Q-statistic was higher than the Q-critical for data at 0° vs 45° and 20° vs 45° indicating that the tilting angles of 0°–45° affected the permeability significantly.

As the panel was tilted, the magnitude of impact force exerted by the air bubbles on the panel varied. The impact force (F_I) imposed by the air bubbles to the membrane panel was largely influenced by the buoyancy force (F_B) and the tilted angle (θ), in which $F_I = F_B \sin \theta$. Based on this equation, the maximum impact force could be obtained once the tilted panel reached 90° which resembled a sinusoidal pattern as depicted in Fig. 3.

The permeability performance was affected by the impact force exerted by the travelling bubbles. Hence, the permeability of tilted membrane reaching 70° was expected to increase until it reached 90°. However, both membrane permeability performance started to drop at tilting angle of 70°, which contradicted with the sinusoidal pattern of impact force as shown in Fig. 3. The lower permeability at tilting angle of 70° compared to 45° can be explained by the congestion of travelling bubbles along membrane panel. The membrane surface would be overcrowded with air bubbles and disrupting the permeate flow, which lowered the permeability (Nawi et al., 2020). This finding implies that system optimization with respect to aeration rate and tilting angle was required to maximize the impact of aeration. Overcrowding the membrane surface with air bubbles under high aeration rates at higher tilting angle would not only reduce the permeability, but also unnecessarily waste aeration energy. The finding suggests the opportunity to couple panel tilting at high tilting angle with a low aeration rate.

This also implies the permeability reached maximum at the tilting angle of 45° due to good membrane cleaning. The air bubbles could remove the foulant via drag force from the membrane more effectively (Eliseus et al., 2018a). Apart from scouring-off the existing foulant, the bubbles also mitigated the accumulation of the foulant materials on the membrane surface (Eliseus et al., 2017). Therefore, tilting the panel at 45° was the optimal angle as it had the highest permeability attained by both membranes.

When comparing the two membranes, tilting the panel at 45° for the PVDF membrane enhanced the permeability significantly by 34% from

Table 1
Summary of polyvinylidene difluoride (PVDF) and polysulfone (PSF) membranes properties.

Parameters	PVDF	PSF
Clean water permeability (L/(m^2·h·bar))	1740 ± 73	923±54
Pore size (μm)	0.42	0.04
Type	Microfiltration	Ultrafiltration
Contact angle (°)	70.5±3	67.9±1
Thickness (μm)	248	261
Morphology	Asymmetric	Asymmetric

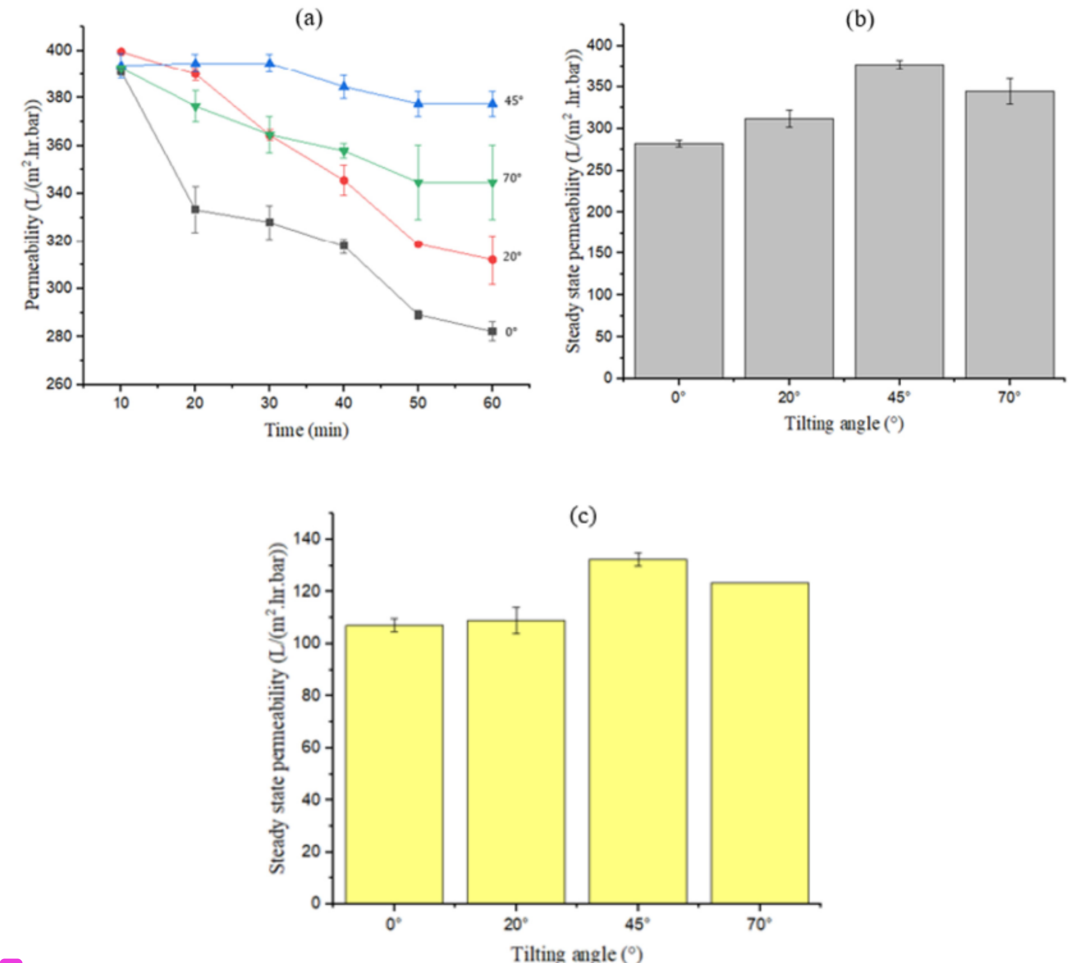

Fig. 2. Effect of tilting angle on (a) PVDF permeability as function of filtration time, (b) steady state permeability of PVDF membrane and (c) PSF membrane. Note that the data for 70° in (c) are identical resulting in zero error.

the vertical panel (tilting angle = 0°). In comparison, PSF membrane panel at a tilting angle of 45° could only improve its permeability from the vertical panel by 24%. This finding was also supported by the one-way ANOVA as it had a p-value of 0.0003 ($p < 0.05$) suggesting that the impact of tilting angle on PVDF and PSF filtration performance were significantly different. Higher permeability of the PVDF membrane can be attributed to its higher pore size than the PSF (Table 1). Membrane with larger pore size had a higher tendency to form irreversible fouling (Lau et al., 2020). Because the PVDF membrane had high fouling propensity, it could still yield remarkably higher permeability than the PSF membrane due to good membrane cleaning. This indicates that the tilted panel system was highly effective in enhancing the permeability of membranes with high (reversible) fouling propensity. Therefore, the PVDF membrane at tilting angle of 45° was selected for further tests.

3.3. Effect of aeration rate

Fig. 4 shows that increasing aeration rate enhanced the permeability and the impact reached plateau at a rate of 1.0 L/min. Beyond plateau permeability, increasing aeration rate no longer enhanced the permeability. It means that the cleaning impact of the air bubbles reached its maximum. The one-way ANOVA conducted in this experiment produced a p-value of 0.00003 ($p < 0.05$) which proved that increasing aeration rate significantly enhanced permeability. The Tukey HSD Test obtained a Q-critical of 5.76 at $\alpha = 0.05$ was lower than the Q-statistic of 0.5 vs 1.0, 0.5 vs 1.2 and 0.5 vs 1.5 L/min implying that the effect of aeration rate was only significant from 0.5 to 1.0 L/min.

The Tukey HSD Test results suggest that further increment of aeration rate beyond 1.0 L/min would not provide a significant increase in permeability. A phenomenon of plateau permeability was also reported elsewhere (Eliseus et al., 2018a).The finding implies that aeration at a rate of 1.0 L/min was enough to remove all reversible foulant from the membrane surface. Besides, exerting excessive shear force was not advised to preserve the quality of the harvested biomass because excessive bubbling could provoke the microalgae cells into releasing AOM that could aggravate membrane fouling (Zhang and Fu, 2018). Hence, the optimum aeration rate for the *Spirulina* sp. medium tested using tilted panel system in this study was in between 0.5 and 1.0 L/min. It is worth noting that albeit the plateau permeability could be reached at aeration rates of 1.0–1.5 L/min, the value could only reach about 500 $L/m^2 \cdot h \cdot bar$ which was about 68% of the clean water permeability value (Table 1). This implies that the aeration supplied was only capable of removing cake layer (reversible fouling). The irreversible fouling (such as pore blocking, and adsorption) could not be removed effectively by

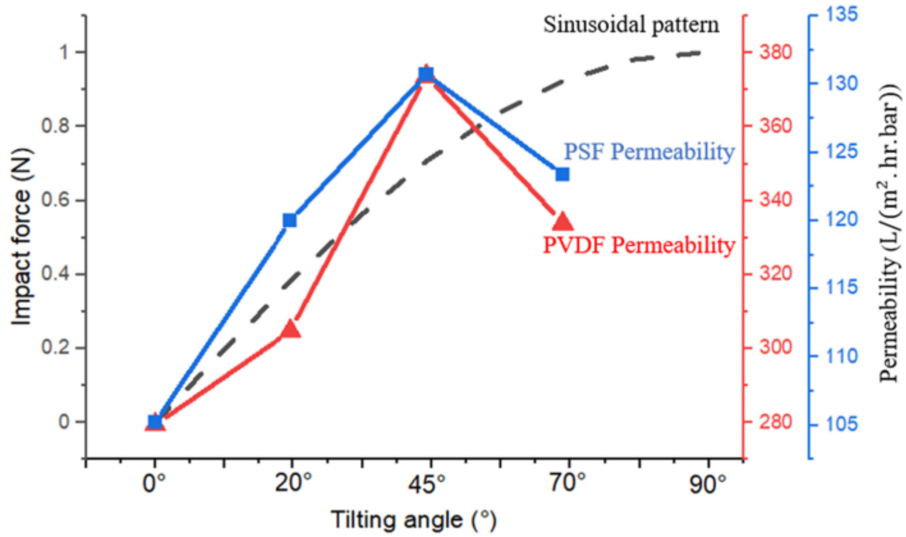

Fig. 3. Permeability at different tilting angle showing the negative impact of overcrowding bubbles at tilting angles above 45°.

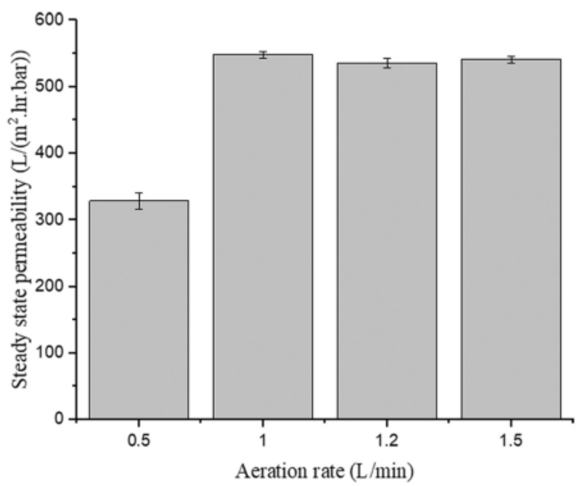

Fig. 4. Effect of aeration rate on PVDF membrane.

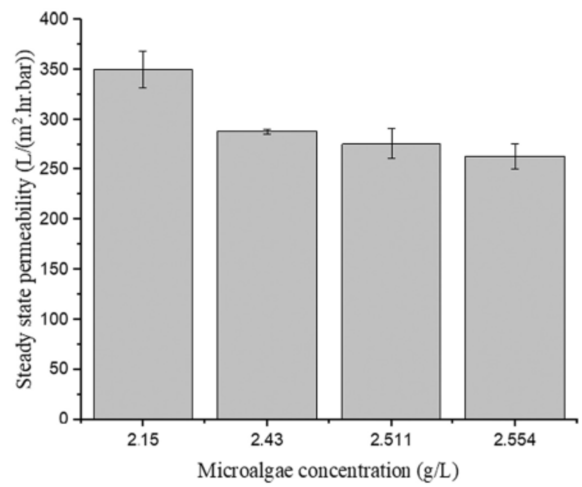

Fig. 5. Effect of microalgae feed concentrations on PVDF permeability.

the induced bubble shear force. Hence, chemical cleaning should be performed in order to restore its pristine membrane permeability.

3.4. Effect of microalgae feed concentration

Fig. 5 shows that the filtration performance was lower at higher biomass concentration. The *Spirulina* sp. broth of 2.15 g/L had the highest permeability whereas the 2.554 g/L had the least permeability. The Tukey HSD analysis between the filtration data of the four concentrations resulted in a Q-critical of 5.76 at $\alpha = 0.05$ which was higher compared to Q-statistic for pair of the groups: 2.43 vs 2.511, 2.43 vs 2.554 and 2.511 vs 2.554 g/L suggesting that within the range of 2.43–2.554 g/L the impact of biomass concentration was insignificant. The Q-critical was lower than Q-statistic only when comparing the 2.15 g/L with the rests, indicating that the influence of concentration was only significantly at a concentration range of 2.15 and 2.43 g/L.

The decreasing trend of permeability at higher concentrations (up to 2.43 in this case) can be explained by the higher AOM concentration accompanied the higher biomass concentration. The presence of AOM was more abundant at higher biomass concentrations causing severe membrane fouling. The biomass fraction alone only imposes a low membrane fouling potential (Discart et al., 2013), but the presence of AOM in the cake layer formation impeded the flow of permeate passing through the cells (Babel and Takizawa, 2010). Besides, high AOM concentration associates with the presence of fouling factor in the form of transparent exopolymer particles (Discart et al., 2015) and an increase in the liquid viscosity.

By considering the negative impact of biomass concentration on the filtration performance, an optimum process design shall be opted. The range of concentration should allow the membrane filtration should operate efficiently, but high enough for effective harvesting since the effectiveness of membrane filtration could be reduced at a very high broth concentration (Bilad et al., 2013). Therefore, it is crucial to identify the optimum concentration for the membrane filtration system by considering its species, operational conditions and membrane characteristics. The membrane-based harvesting can be considered as primary harvesting step to increase the biomass concentration. The thickening process of the biomass can be further continued using a more appropriate process, resulting in two-stage of harvesting (i.e., membrane filtration followed by centrifugation) (Bilad et al., 2014a).

3.5. Energy consumption estimation

The projection of energy consumption for *Spirulina* sp. filtration using the tilted panel system was done to project the energy input required for biomass recovery. A very low energy input is necessary when the biomass is aimed as biofuel feedstock (Sheng et al., 2017). For higher value end products, the energy input is not the main issue but preserving the yield and quality of the target product becomes the priority.

The energy consumption for the *Spirulina* sp. filtration in this study was estimated to be 0.20 kWh/m^3. The energy input was lower than the other membrane filtration for *C. vulgaris* and *P. tricornutum* of 0.27 kWh/m^3 and 0.25 kWh/m^3, respectively (Bilad et al., 2012). Application of an optimized tilted panel system for *Euglena* sp. filtration resulted in energy consumption of 0.238 kWh/m^3 (Eliseus et al., 2018b). This finding suggests that despite operating under sub-optimum condition, the energy input for filtration of the *Spirulina* sp. can be lowered. The low energy input can be attributed to the high flux of 54.4 L/m^2·h at low transmembrane pressure −0.1 bar and moderate aeration rate of 1 L/min. The difference in energy input can also be attributed to the relative filtration performance of microalgae species as detailed elsewhere (Baerdemaeker et al., 2013).

To specifically estimate the energy consumption associated with the aeration, the method developed by Verrecht et al. (2008) was applied, which resulted in a very low aeration energy input of 0.03 kWh/m^3. If this value is used to project the full-scale energy consumption, the total energy input can be further lowered because in a common submerged filtration process, the aeration energy makes up majority of the total energy consumption. Nonetheless, further optimization on the operational parameters are still required. For instance, the filtration cycle of 9/1 (9 min on/1 min relaxation) maybe less attractive in the full-scale.

Table 2
Performance comparison with other studies.

Fouling management system		Microalgae species and concentration	Membrane material (pore size)	Flux L/(m^2 · hr)	Permeability L/(m^2 · hr · bar)	^{a,b}Energy ** (kWh/m^3)	Ref.
Improved air bubbling system	Tilted panel	1.2 g/L of *Spirulina* sp.	PVDF (0.42 µm) PSF (0.04 µm)	55.4 13.3	554 133	0.03^a 0.20^b 0.03^a	This study
	Horizontal panel	1.2–1.4 g/L of *Chlorella* sp.	C-PVDF (0.45 µm) P-PVDF (0.2 µm)	148 210	74 105	–	(Hwang et al., 2015)
	Vertical panel	0.65 g/L of *Chlorella* sp.	MCE (0.22 µm)	11.6–20.5	23.2–41	–	(Alipourzadeh et al., 2016)
	Tilted panel	1 g/L of *Euglena* sp.	PVDF (0.19 µm)	22.5	225	–	(Eliseus et al., 2017)
	Tilted panel	0.6 g/L of *Euglena* sp.	PVDF (0.42 µm)	72	724	0.19^b	(Lau et al., 2020)
	Finned spacer	1.1 ± 0.1 g/L of *C. vulgaris*	PVDF (0.19 ± 0.01 µm)	87 ± 11	870 ± 11	–	(Razak et al., 2020)
Dynamic filtration system	Membrane vibrations	0.25 g/L of *Phaeodactylum* sp. and 0.21 g/L of *Chlorella* sp.	PVDF (0.036 µm) PVDF (0.013 µm)	±21.25–42.5 ±25.5–42.5	212.5–425* 255–425*	0.02^b 0.22^b	(Bilad et al., 2013)
	Axial vibration	0.55 g/L of *C. pyrenoidosa*	PVDF (0.1 µm)	22–64**	220–640	–	(Zhao et al., 2016a)
	Vibration and aeration	0.08 g/L of *Chlorella vulgaris*	PVDF (0.21 µm) PSF (0.13 µm)	32.5	325	–	(Bilad et al., 2014b)
	Axial vibration	0.3 g/L of *C. pyrenoidosa*	PVDF (0.1 µm)	60	85.71	–	(Zhao et al., 2016b)
	Axial vibration and aeration	0.3 g/L of *Chlorella pyrenoidosa*	PVDF (0.1 µm)	238.4	340.57	–	(Zhao et al., 2016c)
	Rotational membrane module	0.06–0.095 g/L of *Phaeodactylum* sp., *Nannochloropsis* sp. and *Chaetoceros* sp.	Ceramic (2 µm) Ceramic (0.5 µm)	460 725 690 430 520 395	230 362.5 345 215 260 197.5	–	(Ríos et al., 2012)
	Vibration shear enhanced process	1.1 g/L of *Dunaliella tertiolecta*	PAN50 PE5 ABS	490 ± 20 164.5 ± 7 18.9 ± 0.2	140 ± 20 47 ± 7 5.4 ± 0.2	–	(Hapońska et al., 2018)
	Rotated disk module	1 g/L of *Parachlorella kessleri*	PES (200 kDa) PAN (500 kDa) PVDF (0.4 µm) PVDF (1.5 µm)	36± 4 29 ± 8 57 ± 20 55 ± 13	90 ± 4 48.3–58 ± 8 142.5 ± 20 91.7–110 ± 13	–	(Villafaña-López et al., 2019)
	Vibration module	1.2 ± 0.2 g/L of *Dictyosphaerium* sp.	12% wt PVDF (0.013 µm)	46**	460	0.21^b	(Zhao et al., 2020)
Physical cleaning	Submerged disc	10.0 g/L of *Spirulina* sp.	PVDF (10–40 nm)	57–143	95–238.3	12.72^b	(Kanchanatip et al., 2016)
	Backwashing and ventilation	0.968 g/L of *Scenedesmus* sp.	PVDF (0.2 µm)	130	260	–	(Chen et al., 2012)
	Submerged microfiltration	0.41 ± 0.05 g/L of *Chlorella vulgaris* 0.23 ± 0.06 g/L of *Phaeodactylum* sp.	PVDF (0.36 µm)	32–50	320–500	0.27^b 0.25^b	(Bilad et al., 2012)
	Backwashing	2.9 g/L of *Chlorella* sp.	HF PVC (0.01 µm)	70	202.9	–	(Zhang et al., 2013)

When no TMP data is available, the permeability was calculated from the reported flux (*) or critical flux (**) by assuming the TMP 0.1 bar. HF (hollow fiber), Polyvinyl chloride (PVC), Commercial PVDF (C-PVDF), Porous PVDF (P-PVDF), Micro cellulose ester (MCE), Commercial polyethersulfone (PE5), Commercial polyacrylonitrile (PAN50), and Self-made acrylonitrile butadiene styrene (ABS). The energy refers to (^{a}) aeration energy and (^{b}) total energy.

Application of relaxation at high solid concentration can be vulnerable from clogging of the perforated pipe typically used to supply membrane aeration.

3.6. Comparison with other studies

Table 2 summarizes the performance of microalgae filtration in fouling control management from recent literature. To the best of our literature search, there is no report available on *Spirulina* sp. broth filtration. Therefore, the comparison most of the studies were carried out for the filtration of *Euglena* sp. and *Chlorella* sp. as the microalgae feed. The tilted panel system using PVDF membrane in this study showed significantly higher permeability than other fouling control strategies, such as physical cleaning and DMF (Razak and Bilad, 2021). The maximum permeability obtained by the membrane vibration was 460 L/(m^2·hr·bar) (Zhao et al., 2020) and the physical cleaning was 500 L/(m^2·hr·bar) (Bilad et al., 2012). When compared, this study had 20.4% and 10.8% higher. This comparison clearly revealed that the air bubbling system was an effective fouling control strategy for *Spirulina* sp. filtration as compared to others.

Under the air bubbling control system, there were two previous reports that assessed the performance of tilted panel configuration as well. The first study on tilted panel setup yielded a maximum permeability of 225 L/(m^2·hr·bar) which was 59.4% lower than the current study. This could be due to the limited tilting angle at 20°, different type of microalgae, broth concentration, and membrane pore size. In the subsequent study, the permeability obtained was 23.5% greater than this study, in spite of using smaller tilting angle than the current study (20° vs 45°), and identical membrane type and pore size. The other factors that might vary the permeability could be due to different microalgae species and concentration.

The permeability achieved in this study was still lower when compared among other air bubbling control systems. This study obtained a maximum permeability of 554 L/(m^2·hr·bar) which was 36% lower than the maximum permeability gained by the finned spacer membrane filtration of 870 L/(m^2·hr·bar) during filtration of *C. vulgaris* (Razak et al., 2020). Both systems incorporated air bubbling system but with different configurations. Nevertheless, this was not a direct comparison as both systems had different microalgae species, operational parameters, and configurations. In general, it can be seen that the findings on the permeability in this study were within the upper range of the results reported in the literature. Nonetheless, the filtration energy input was the lowest reported so far.

Overall results demonstrate the efficacy of the tilted panel system for fouling control in *Spirulina* sp. biomass filtration. The performance of the system can be enhanced using a more permeable PVDF membrane and can be optimized under certain aeration rate (between 0.5 and 1.0 L/min) and certain biomass concentration. Considering the energy consumption reported in Table 2, PVDF membrane under tilted panel system is economically attractive to boost the economic advantage of *Spirulina* sp. for food purpose. Since the *Spirulina* sp. biomass is marketed as a dry powder, membrane-based process can be used to concentrate the biomass from the cultivation medium to remove the majority of the water prior to thickening and drying processes. The permeate water can be reused for subsequent cultivation in which the excess nutrients can be utilized as well. This water reuse lowers the production cost in term of feed water sterilization as well as reduces the need of the fresh nutrients.

4. Conclusions

This study concludes that the tilted panel system was an effective and energy-efficient for harvest *Spirulina* sp. The permeability peaked at the tilting angle of 45° in accord with the proposed model. Optimal aeration occurred in the range of 0.5–1.0 L/min. Filtration of a higher *Spirulina* sp. concentration yielded a lower permeability. The estimated total energy consumption of the *Spirulina* sp. broth solution was 0.20 kWh/m^3, the lowest reported so far which can still be reduced further from the independent results of aeration energy estimation of merely 0.03 kWh/m^3.

Funding

This research was funded by Yayasan Universiti Teknologi PETRONAS, Malaysia, grant number 015LC0-193.

CRediT authorship contribution statement

Insyirah Ismail performed all the experiments and prepared the manuscript draft; Muhammad Roil Bilad contributed to the original idea of the study, conceptually design the study and revised the manuscript; Lisendra Marbelia, Shafirah Samsuri, and Arief Budiman developed the experimental setup, supervised the experiment and validated the experimental results; Lisendra Marbelia, Kiki Adi Kurnia, Noor Maizura Ismail, Asim Laeeq Khan and Susilawati Susilawati revised the manuscript.

Declaration of competing interest

The authors declare no conflict of interest.

References

Alipourzadeh, A., Mehrnia, M.R., Sani, A.H., Babaei, A., 2016. Application of response surface methodology for investigation of membrane fouling behaviours in microalgal membrane bioreactor: the effect of aeration rate and biomass concentration. RSC Adv. 6, 111182–111189. https://doi.org/10.1039/C6RA23188H.

Andrade, L.M., 2018. Chlorella and Spirulina microalgae as sources of functional foods, nutraceuticals, and food supplements; an overview. MOJ Food Process. Technol. 6, 45–58. https://doi.org/10.15406/mojfpt.2018.06.00144.

Azma, M., Mohamed, M.S., Mohamad, R., Rahim, R.A., Ariff, A.B., 2011. Improvement of medium composition for heterotrophic cultivation of green microalgae, Tetraselmis suecica, using response surface methodology. Biochem. Eng. J. 53, 187–195. https://doi.org/10.1016/j.bej.2010.10.010.

Babel, S., Takizawa, S., 2010. Microfiltration membrane fouling and cake behavior during algal filtration. Desalination 261, 46–51. https://doi.org/10.1016/j.desal.2010.05.038.

Baerdemaeker, T.D., Lemmens, B., Dotremont, C., Fret, J., Roef, L., Goiris, K., Diels, L., 2013. Benchmark study on algae harvesting with backwashable submerged flat panel membranes. Bioresour. Technol. 129, 582–591. https://doi.org/10.1016/j.biortech.2012.10.153.

Bilad, M.R., Vandamme, D., Foubert, I., Muylaert, K., Vankelecom, I.F.J., 2012. Harvesting microalgal biomass using submerged microfiltration membranes. Bioresour. Technol. 111, 343–352. https://doi.org/10.1016/j.biortech.2012.02.009.

Bilad, M.R., Discart, V., Vandamme, D., Foubert, I., Muylaert, K., Vankelecom, I.F.J., 2013. Harvesting microalgal biomass using a magnetically induced membrane vibration (MMV) system: Filtration performance and energy consumption. Bioresour. Technol. 138, 329–338. https://doi.org/10.1016/j.biortech.2013.03.175.

Bilad, M.R., Arafat, H.A., Vankelecom, I.F.J., 2014a. Membrane technology in microalgae cultivation and harvesting: a review. Biotechnol. Adv. 32, 1283–1300. https://doi.org/10.1016/j.biotechadv.2014.07.008.

Bilad, M.R., Marbelia, L., Naik, P., Laine, C., Vankelecom, I.F.J., 2014b. Direct comparison of aerated and vibrated filtration systems for harvesting of Chlorella vulgaris. Algal Res. 6, 32–38. https://doi.org/10.1016/j.algal.2014.09.001.

Chen, X., Huang, C., Liu, T., 2012. Harvesting of microalgae Scenedesmus sp. using polyvinylidene fluoride microfiltration membrane. Desalination Water Treat. 177–181. https://doi.org/10.1080/19443994.2012.692034.

Cheng, T.-W., 2002. Influence of inclination on gas-sparged cross-flow ultrafiltration through an inorganic tubular membrane. J. Membr. Sci. 196, 103–110. https://doi.org/10.1016/S0376-7388(01)00584-1.

de Jesus, C.S., da Silva Uebel, L., Costa, S.S., Miranda, A.L., de Morais, E.G., de Morais, M.G., Costa, J.A.V., Nunes, I.L., de Souza Ferreira, E., Druzian, J.I., 2018. Outdoor pilot-scale cultivation of Spirulina sp. LEB-18 in different geographic locations for evaluating its growth and chemical composition. Bioresour. Technol. 256, 86–94. https://doi.org/10.1016/j.biortech.2018.01.149.

Discart, V., Bilad, M.R., Vandamme, D., Foubert, I., Muylaert, K., Vankelecom, I.F.J., 2013. Role of transparent exopolymeric particles in membrane fouling: Chlorella vulgaris broth filtration. Bioresour. Technol. 129, 18–25. https://doi.org/10.1016/j.biortech.2012.11.034.

Discart, V., Bilad, M.R., Vankelecom, I.F.J., 2015. Critical evaluation of the determination methods for transparent exopolymer particles, agents of membrane fouling. Crit. Rev. Environ. Sci. Technol. 45, 167–192. https://doi.org/10.1080/10643389.2013.829982.

Eliseus, A., Bilad, M.R., Nordin, N.A.H.M., Putra, Z.A., Wirzal, M.D.H., 2017. Tilted membrane panel: a new module concept to maximize the impact of air bubbles for

membrane fouling control in microalgae harvesting. Bioresour. Technol. 241, 661–668. https://doi.org/10.1016/j.biortech.2017.05.175.
Eliseus, A., Bilad, M.R., Nordin, N.A.H.M., Khan, A.L., Putra, Z.A., Wirzal, M.D.H., Aslam, M., Aqsha, A., Jaafar, J., 2018a. Two-way switch: maximizing productivity of tilted panel in membrane bioreactor. J. Environ. Manag. 228, 529–537. https://doi.org/10.1016/j.jenvman.2018.09.029.
Eliseus, A., Putra, Z.A., Bilad, M.R., Nordin, N.A.H.M., Wirzal, M.D.H., Jaafar, J., Khan, A.L., Aqsha, 2018b. Energy minimization of a tilted panel filtration system for microalgae filtration: Performance modeling and optimization. Algal Res. 34, 104–115. https://doi.org/10.1016/j.algal.2018.07.008.
Fenu, A., Roels, J., Wambecq, T., De Gussem, K., Thoeye, C., De Gueldre, G., Van De Steene, B., 2010. Energy audit of a full scale MBR system. Desalination 262, 121–128. https://doi.org/10.1016/j.desal.2010.05.057.
Hapońska, M., Clavero, E., Salvadó, J., Farriol, X., Torras, C., 2018. Pilot scale dewatering of Chlorella sorokiniana and Dunaliella tertiolecta by sedimentation followed by dynamic filtration. Algal Res. 33, 118–124. https://doi.org/10.1016/j.algal.2018.05.007.
Hwang, T., Oh, Y.K., Kim, B., Han, J.I., 2015. Dramatic improvement of membrane performance for microalgae harvesting with a simple bubble-generator plate. Bioresour. Technol. 186, 343–347. https://doi.org/10.1016/j.biortech.2015.03.111.
Kanchanatip, E., Su, B.-R., Tulaphol, S., Den, W., Grisdanurak, N., Kuo, C.-C., 2016. Fouling characterization and control for harvesting microalgae Arthrospira (Spirulina) maxima using a submerged, disc-type ultrafiltration membrane. Bioresour. Technol. 209, 23–30. https://doi.org/10.1016/j.biortech.2016.02.081.
Lau, A.K.S., Bilad, M.R., Nordin, N.A.H.M., Faungnawakij, K., Narkkun, T., Wang, D.K., Mahlia, T.M.I., Jaafar, J., 2020. Effect of membrane properties on tilted panel performance of microalgae biomass filtration for biofuel feedstock. Renew. Sust. Energ. Rev. 120, 109666 https://doi.org/10.1016/j.rser.2019.109666.
Lee, J., Ahn, W.-Y., Lee, C.-H., 2001. Comparison of the filtration characteristics between attached and suspended growth microorganisms in submerged membrane bioreactor. Water Res. 35, 2435–2445. https://doi.org/10.1016/S0043-1354(00)00524-8.
Li, H., Li, Z., Xiong, S., Zhang, H., Li, N., Zhou, S., Liu, Y., Huang, Z., 2011. Pilot-scale isolation of bioactive extracellular polymeric substances from cell-free media of mass microalgal cultures using tangential-flow ultrafiltration. Process Biochem. 46, 1104–1109. https://doi.org/10.1016/j.procbio.2011.01.028.
Nawi, N.I.M., Sivalingam, S., Bilad, M.R., 2020. Fouling control via horizontal membrane panel for activated sludge filtration. J. Eng. Pract. 2, 1–6.
Osman, A., Mat Nawi, N.I., Samsuri, S., Bilad, M.R., Shamsuddin, N., Khan, A.L., Jaafar, J., Nordin, N.A.H., 2020. Patterned membrane in an energy-efficient tilted panel filtration system for fouling control in activated sludge filtration. Polymers 12, 432. https://doi.org/10.3390/polym12020432.
Razak, Nik Nurul Ain Nabilah, Bilad, Muhammad Roil, 2021. Progress in development of Membrane Fouling Control for Microalgae Filtration: a Review. Jurnal Penelitian dan Pengkajian Ilmu Pendidikan: e-Saintika 5 (1), 67–91. https://doi.org/10.36312/e-saintika.v5i1.424.
Razak, N.N.A.N., Rahmawati, R., Bilad, M.R., Pratiwi, A.E., Elma, M., Nawi, N.I.M., Jaafar, J., Lam, M.K., 2020. Finned spacer for enhancing the impact of air bubbles for membrane fouling control in Chlorella vulgaris filtration. Bioresour. Technol. Rep. 11, 100429 https://doi.org/10.1016/j.biteb.2020.100429.
Ríos, S.D., Salvadó, J., Farriol, X., Torras, C., 2012. Antifouling microfiltration strategies to harvest microalgae for biofuel. Bioresour. Technol. 119, 406–418. https://doi.org/10.1016/j.biortech.2012.05.044.
Sheng, A.L.K., Bilad, M.R., Osman, N.B., Arahman, N., 2017. Sequencing batch membrane photobioreactor for real secondary effluent polishing using native microalgae: Process performance and full-scale projection. J. Clean. Prod. 168, 708–715. https://doi.org/10.1016/j.jclepro.2017.09.083.
Silva, N.C., Machado, M.V.C., Brandão, R.J., Duarte, C.R., Barrozo, M.A.S., 2019. Dehydration of microalgae Spirulina platensis in a rotary drum with inert bed. Powder Technol. 351, 178–185. https://doi.org/10.1016/j.powtec.2019.04.025.
Tan, X., Rodrigue, D., 2019. A review on porous polymeric membrane preparation. Part II: production techniques with polyethylene, polydimethylsiloxane, polypropylene, polyimide, and polytetrafluoroethylene. Polymers 11, 1310. https://doi.org/10.3390/polym11081310.
Tang, D.Y.Y., Khoo, K.S., Chew, K.W., Tao, Y., Ho, S.H., Show, P.L., 2020. Potential utilization of bioproducts from microalgae for the quality enhancement of natural products. Bioresour. Technol. 304, 122997 https://doi.org/10.1016/j.biortech.2020.122997.
Tian, J., Xu, Y., Chen, Z., Nan, J., Li, G., 2010. Air bubbling for alleviating membrane fouling of immersed hollow-fiber membrane for ultrafiltration of river water. Desalination 260, 225–230. https://doi.org/10.1016/j.desal.2010.04.026.
Vaz, B. da S., Moreira, J.B., Morais, M.G. de, Costa, J.A.V., 2016. Microalgae as a new source of bioactive compounds in food supplements. Curr. Opin. Food Sci., Food Chemistry and Biochemistry • Food Bioprocessing 7, 73–77. https://doi.org/10.1016/j.cofs.2015.12.006.
Verrecht, B., Judd, S., Guglielmi, G., Brepols, C., Mulder, J.W., 2008. An aeration energy model for an immersed membrane bioreactor. Water Res. 42, 4761–4770. https://doi.org/10.1016/j.watres.2008.09.013.
Villafaña-López, L., Clavijo Rivera, E., Liu, S., Couallier, E., Frappart, M., 2019. Shear-enhanced membrane filtration of model and real microalgae extracts for lipids recovery in biorefinery context. Bioresour. Technol. 288, 121539 https://doi.org/10.1016/j.biortech.2019.121539.
Zhang, Y., Fu, Q., 2018. Algal fouling of microfiltration and ultrafiltration membranes and control strategies: a review. Sep. Purif. Technol. 203, 193–208. https://doi.org/10.1016/j.seppur.2018.04.040.
Zhang, Wei, Zhang, Wen, Zhang, X., Amendola, P., Hu, Q., Chen, Y., 2013. Characterization of dissolved organic matters responsible for ultrafiltration membrane fouling in algal harvesting. Algal Res. 2, 223–229. https://doi.org/10.1016/j.algal.2013.05.002.
Zhao, F., Chu, H., Su, Y., Tan, X., Zhang, Y., Yang, L., Zhou, X., 2016a. Microalgae harvesting by an axial vibration membrane: the mechanism of mitigating membrane fouling. J. Membr. Sci. 508, 127–135. https://doi.org/10.1016/j.memsci.2016.02.007.
Zhao, F., Chu, H., Tan, X., Yang, L., Su, Y., Zhou, X., Zhao, J., Zhang, Y., 2016b. Using axial vibration membrane process to mitigate membrane fouling and reject extracellular organic matter in microalgae harvesting. J. Membr. Sci. 517, 30–38. https://doi.org/10.1016/j.memsci.2016.06.022.
Zhao, F., Chu, H., Tan, X., Zhang, Y., Yang, L., Zhou, X., Zhao, J., 2016c. Comparison of axial vibration membrane and submerged aeration membrane in microalgae harvesting. Bioresour. Technol. 208, 178–183. https://doi.org/10.1016/j.biortech.2016.02.099.
Zhao, Z., Mertens, M., Li, Y., Muylaert, K., Vankelecom, I.F.J., 2020. A highly efficient and energy-saving magnetically induced membrane vibration system for harvesting microalgae. Bioresour. Technol. 300, 122688 https://doi.org/10.1016/j.biortech.2019.122688.

Energy effiient harvesting of Spirulina sp. from the growth medium using a tilted panel membrane fitration

ORIGINALITY REPORT

2%	%	%	2%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Submitted to University of the Andes Student Paper	1%
2	Submitted to Universiti Teknologi Petronas Student Paper	<1%
3	Submitted to School of Business and Management ITB Student Paper	<1%
4	Submitted to Meerut Institute of Engineering & Technology Student Paper	<1%
5	Submitted to CSU, Long Beach Student Paper	<1%
6	Submitted to University of Lancaster Student Paper	<1%
7	Submitted to University of Alabama at Birmingham Student Paper	<1%