Aquacultural Engineering 98 (2022) 102269

Contents lists available at ScienceDirect

Aquacultural Engineering

journal homepage: www.elsevier.com/locate/aque

Microalgae cultivation in offshore floating photobioreactor: State-of-the-art, opportunities and challenges

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ARTICLE INFO

Keywords:
Microalgae cultivation
Floating photobioreactor
Offshore technology
Mixing
Wave energy
Biomass production

ABSTRACT

The wide application of microalgae in health foods, nutritional feeds, aquaculture, pharmaceutical extracts, and biofuel production, has brought about the advancement of the microalgae cultivation industry. However, commercial-scale cultivation of microalgae still faces one major challenge, which is its economic feasibility, with lower cost and energy consumption. Developing floating photobioreactors to be utilized in offshore open water areas has gained more interest recently as it can diminish the cost effects of onshore land utilization, while seeking for additional benefits, such as regulated temperature, proximity to sunlight and nutrient supplies, and integrated ocean renewable energy. Thereby, this is timely to explore the potential of floating photobioreactors for microalgae cultivation in the offshore region. This review deliberately presents the characteristics of offshore environments and their potential effects on microalgae cultivation, as factors such as location selection, heat capacity, and utilization of cultivation resources are significantly different from conventional land-based cultivation. Compared to land-based photobioreactors, the design of floating photobioreactors has the opportunity to adopt hydrodynamical design; by utilizing the external force from ocean waves to generate internal liquid sloshing for improving the mixing of cultivation medium. While offshore-based microalgae cultivation is considerably new as part of blue economy and mariculture, this review provides insights into the opportunities for further advancement of offshore microalgae cultivation technologies. The encouraging factors for hybridization of offshore microalgae cultivation include mariculture, carbon dioxide capture and utilization, hydrogen production, and ocean thermal energy. Such understandings are vital to improving microalgae cultivation in offshore floating photobioreactors towards a valuable alternative to the current concerns in developing commercial scale of the microalgae industry. Various challenges in biological issues, economic and environmental challenges, installation and maintenance, as well as destructive hydrodynamic loads are also discussed.

Abbreviations: BOD, Biological Oxygen Demand; *C. vulgaris*, Chlorella vulgaris; CFD, Computational Fluid Dynamics; cm/s, Centimetre per second; CO_2, Carbon dioxide; EROI, Energy Return on Investment; g/L, Gram per litre; g/L/day, Gram per litre per day; g/m2/day, Gram per meter square per day; GHG, Greenhouse gases; Hz, Hertz; kg m^{-2}, Kilograms per meter square; kWh, Price per kilowatt hour; l, Litre; LDPE, low-density polyethylene; m, Meters; m/s, Meter per second; M/y, Million per year; m^{-1}, Per square; m^2, Meter square; mg, Milligram; MJ, Megajoules; ml, Milli litre; NASA, National Aeronautics and Space Administration; OMEGA, Offshore Membrane Enclosures for Growing Algae; OTEC, Ocean Thermal Energy Conversion; PBR, Photobioreactor; PET, polyethylene terephthalate; PVC, Polyvinyl Chloride; RR, Revenue required; s, Second; SDG, Sustainable Development Goals; *sp.*, species; tonnes/ha/year, Tonnes per hectare per year; USD, US Dollar; vvm, Volume of liquid per minute.

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https://doi.org/10.1016/j.aquaeng.2022.102269
Received 23 October 2021; Received in revised form 1 June 2022; Accepted 7 June 2022

1. Introduction

Microalgae biotechnology is a potential alternative to tackle various concerns with regards to rapidly developing human society, such as food security, energy crisis, global warming, and waste management. Out of 17 Sustainable Development Goals (SDGs) by United Nations, algae technologies addresses at least 7 SDGs, including securing clean water and sanitation, ensuring good health and well-being, encouraging affordable and clean energy, combat against climate action, and promoting sustainable cities and communities, besides preservation of life below water and life on land (Phang, 2018). Numerous studies on microalgae biotechnology have shown its possibilities to replace land crops for meal nutrients, renewable energy, animal and aquaculture feeds, value-added products and chemicals, as well as contributing to carbon utilization and sewage treatment (Dębowski et al., 2020; Shekh et al., 2022; Tossavainen et al., 2019). The wide range of microalgae applications has led to the advancement of microalgae cultivation technology.

Microalgae cultivation has been a major emphasis in the study of microalgae biotechnology, with a rapid increase in published articles since 2010, and totalling 770 articles in the year of 2020. Although research of microalgae cultivation floating on open waters has been steadily refined since 2010 and showing an increasing trend, the number of articles published is still far fewer compared to land-based photobioreactor technologies, as shown in Fig. 1(a). For over more than 60 years, commercialized microalgae cultivation has been conducted in natural open waters or man-made ponds. Starting from simple shallow basins to open systems and the advancement of closed systems, land-based cultivation systems have been researched more thoroughly compared to floating cultivation technologies. As presented in Fig. 1(b), floating cultivation technologies are still considered as a new field with only 3 % articles published in 2021, compared to land-based cultivation technologies, which accounts up to 92 % of the articles published concerning microalgae cultivation. From Fig. 1(c), the innovative development of PBR geometry mainly focus on traditional PBRs, such as tubular, tanks and flat plate geometries. However, only about 20 % of

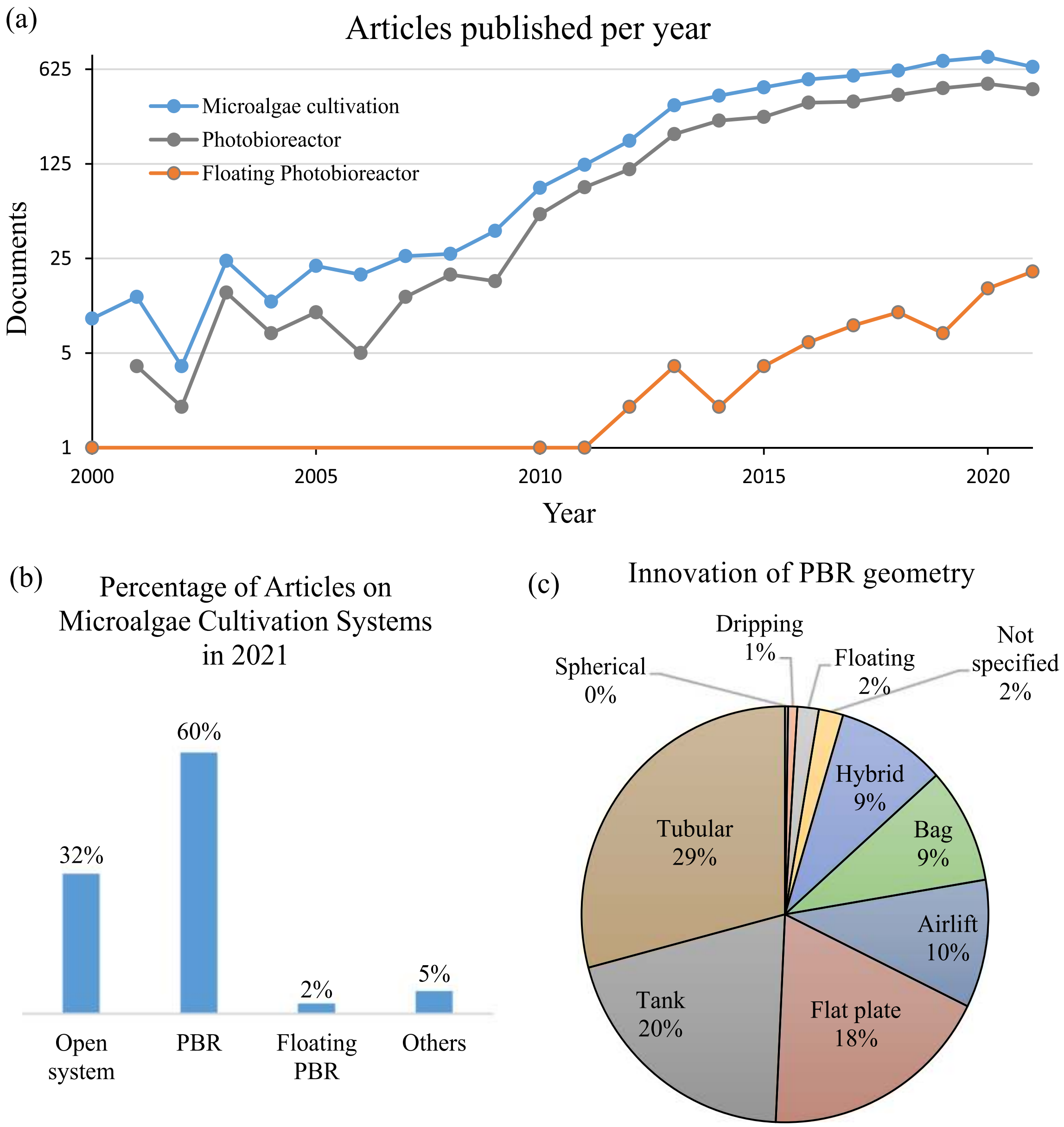


Fig. 1. (a) Documents per year for published "Microalgae cultivation", "Photobioreactor" and "Floating Photobioreactor" articles, (b) Percentage of articles on microalgae cultivation systems in year 2021, (c) Innovation of PBR geometry (Kirnev et al., 2020).
(b) (Data retrieved on 17 August 2021 from Scopus)

the innovative PBR geometry are emerging PBRs to reduce the expenses on temperature control and material, such as hybrid PBR, floating PBRs and bag PBRs (Kirnev et al., 2020). Researches on floating photobioreactors have been mainly focused on lab scale researches and application in coastal waters (Wiley et al., 2013; Zittelli et al., 2013), therefore there is a need to further explore this new field to appraise the potential of floating photobioreactors for development of the ocean economy.

Described as sunlight-driven factories, microalgae can convert organic and/or inorganic carbons into useful biomass that can produce diverse variety of products, ranging from low price products, for instance, biofuels, animal and aquaculture feed, to high-price substances, for example, pigments, pharmaceutical compounds, cosmetic lipids, and bioactive compounds (Chisti, 2007; Mathimani and Pugazhendhi, 2019; Rösch et al., 2019). According to Trivedi et al. (2015), microalgae applications can be divided into energy products, non-energy products, and environmental applications (Dębowski et al., 2020; Tossavainen et al., 2019; Trivedi et al., 2015), as shown in Fig. 2. Types of energy products include biodiesel, bioethanol, biogas, and bio-jet fuel, while non-energy products include carbohydrates, protein, pigments, bioproducts and biomaterials. Microalgae can be integrated into different systems for environmental cleaning purposes, such as biological utilization of CO_2 to mitigate CO_2 from flue gas emissions from industrial units, and bio-remediation of wastewater and polluted soil (Khan et al., 2018; Nguyen et al., 2021).

Common land-based cultivation technologies to cultivate phototrophic microalgae can be mainly categorized into open systems, closed systems and hybrid systems (Sirohi et al., 2022), as shown in Fig. 3. The most commonly used commercialize systems focusing on the production of particular microalgae species are open ponds, such as circular ponds and raceway ponds (Kumar et al., 2015), while closed systems (Gupta and Choi, 2015), for example, flat plate PBR, column PBR, and tubular PBR, which have more control of cultivation conditions, are frequently used to yield high value products, due to better control of contamination (Erbland et al., 2020; Wang et al., 2012). Alternatively, hybrid systems are designed mainly to bring together the strengths of both open systems and closed systems to increase efficiency and reduce capital cost (Assunção and Malcata, 2020; Belohlav, Uggetti, García, Jirout, Kratky and Díez-Montero, 2021; Narala et al., 2016; Xiong et al., 2021). Table 1 displays the differences between open, closed and hybrid systems, while Table 2 exhibits the variations of space consumption and obtainable biomass productivity between open systems and closed PBRs. Similarly, floating PBRs (Zhu et al., 2019c) are systems developed to be placed on open water surface instead of land-based structures as well as reducing capital and operational costs.

Floating photobioreactors are introduced to utilize the vast open water surface to overcome the issue of limited land area, along with additional advantages such as complimentary temperature regulation, and unsettled water surface providing mixing energy and resourceful nutrients. For instance, the unsettling motion of PBR floating on the water surface due to current and ocean waves provides mixing energy to the culture medium from ocean renewable source (Zhu et al., 2018b). The offshore cultivation system also benefits from resourceful nutrients (Park et al., 2018; Toyoshima et al., 2015), wide unexploited space (Phang, 2018; Thangavel and Sridevi, 2015), and complimentary temperature regulation. The concept of floating PBRs could potentially replace conventional cultivation systems, due to more competent productivity of microalgae biomass, and substantially lower cost compared to land-based cultivation systems in terms of capital costs, operational costs and expenditure on maintenance (Dogaris et al., 2015; Huang et al., 2016; Zhu et al., 2014).

Reviews on microalgae cultivation include microalgae strains (Chew et al., 2018; Okoro et al., 2019), growth modes and cultivation conditions (Brennan and Owende, 2010; Vuppaladadiyam et al., 2018), designs and technologies of cultivation systems (Assunção and Malcata, 2020; Carvalho et al., 2006; Chen, Yeh, Aisyah, Lee and Chang, 2011; Pires et al., 2017; Weissman et al., 1988), cultivation parameters and influencing factors of microalgae cultivation (Bitog et al., 2011; Carvalho, Silva, Baptista and Malcata, 2011; Hossain and Mahlia, 2019; Juneja et al., 2013; Teoh et al., 2010; Wang and Lan, 2018), harvesting and extraction (Bilad et al., 2014; Mujeeb et al., 2016; Tan et al., 2020), wastewater treatment and carbon sequestration (Luo et al., 2017; Nie et al., 2020; Vo et al., 2019; Zhou et al., 2017), and commercial applications of microalgae (Bekirogullari, Figueroa-Torres, Pittman and Theodoropoulos, 2020; Dębowski et al., 2020; Kratzer and Murkovic, 2021; Mata et al., 2010; Morais Junior et al., 2020; Rizwan et al., 2018; Sirakov et al., 2015). Majority of the reviews discussed about land-based systems, such as open systems, closed systems, hybrid systems, and sporadically floating systems. Floating systems are often discussed under the category of other cultivation systems, and rarely discussed particularly. Nevertheless, a recent review by Zhu et al. (2019b) discussed about the design and recent advancements of floating photobioreactors, besides examining the drawbacks and challenges of floating photobioreactors for commercial purposes. The review concludes that microalgae cultivation on open water surface is an encouraging alternative to overcome land space limitations. As a relatively new research field, the lack of reviews and growing interest on floating photobioreactors for microalgae cultivation has led to the purpose of writing this review, which is to explore more possibilities of microalgae cultivation in the broad offshore territory; not only considering coastal

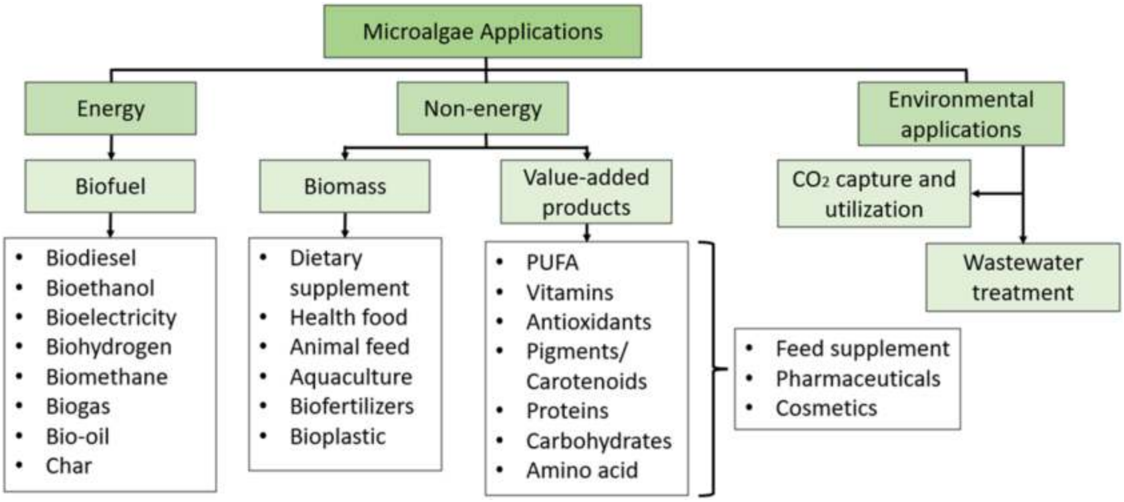


Fig. 2. Applications of microalgae (Priyadarshani and Rath, 2012; Rizwan et al., 2018; Sirohi et al., 2022; Spolaore et al., 2006).

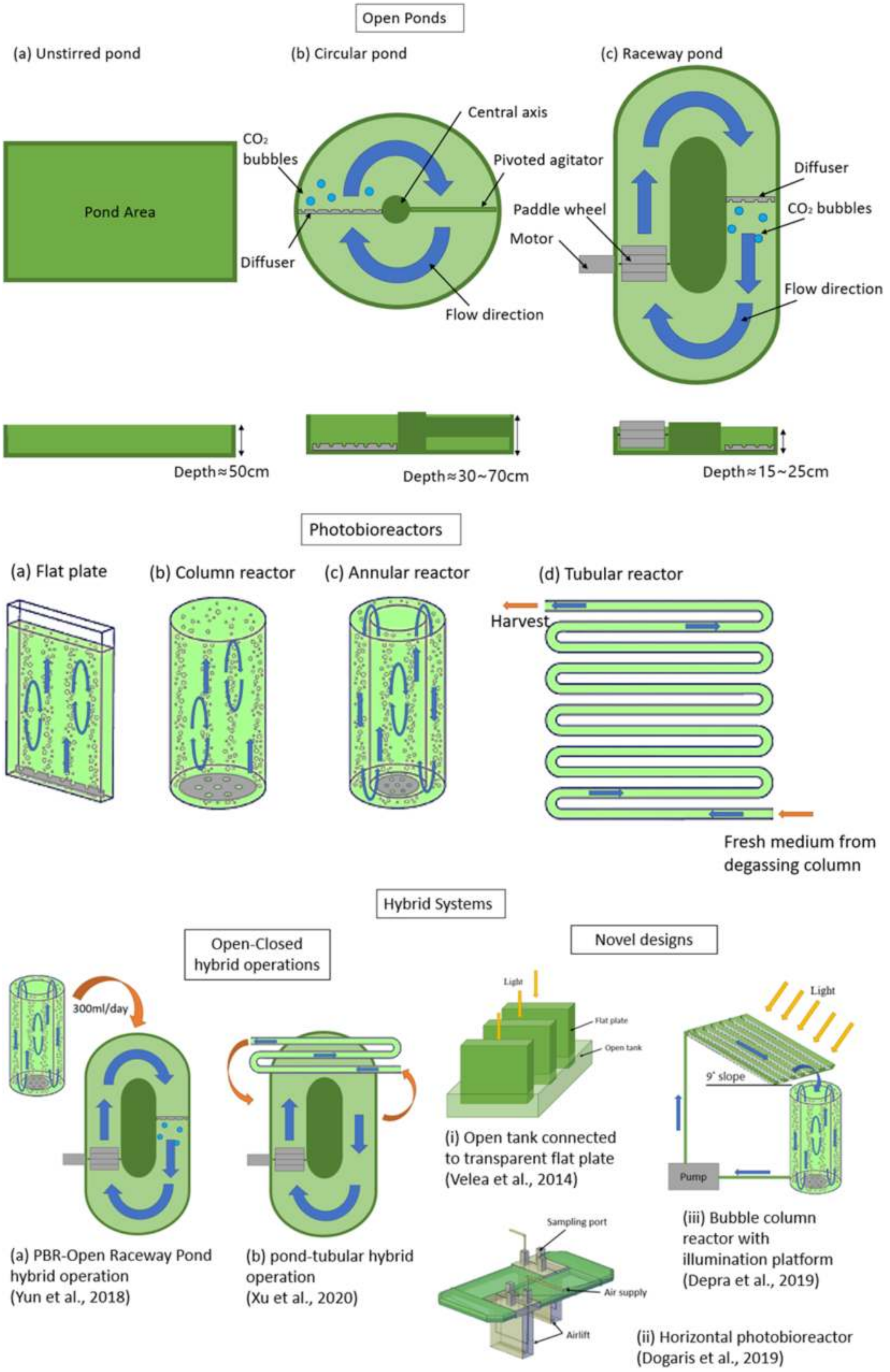


Fig. 3. Microalgae cultivation systems for phototrophic cultivation (Hallmann, 2015; Suparmaniam et al., 2019; Zerrouki and Henni, 2019).

Table 1
Comparison of open, closed and hybrid algae cultivation systems.

Criterion	Open systems	Closed systems	Hybrid systems	Ref.
Space required	High	Moderate	Moderate	(Chisti, 2007)
Area/volume ratio	20–200 m-1	5–10 m-1	7–50 m-1	(Campo et al., 2007; Mata et al., 2010)
Maintenance	Easy	Difficult	Moderate	(Ugwu et al., 2008)
Period to achieve net production	6–8 weeks	2–4 weeks	1–2 weeks	(Pulz, 2001)
Biomass concentration	0.1–0.2 g/L	2–8 g/L	2–8 g/L	(Pulz, 2001)
Biomass quality	Non-consistent	Consistent	Consistent	(Pulz, 2001)
Risk of contamination	High	Low	Moderate	(Campo et al., 2007; Pulz, 2001)
Cultivation method	Batch / Semi-continuous	Batch/ Continuous	Batch/ Continuous/ Semi-continuous	(Campo et al., 2007; Mata et al., 2010)
Capital cost	8–55 USD/m^3	685–2065 USD/m^3	11–30 USD/m^3	(Delrue et al., 2012; Mata et al., 2010)
Energy consumption	$\sim$3.7 W/m^3	53–2500 W/m^3	$\sim$52 W/m^3	(Deprá et al., 2019; Jorquera et al., 2010)
Species variability	Limited	High variability	High variability	(Mata et al., 2010; Pulz, 2001)
Water evaporation losses	High	Low	Moderate	(Mata et al., 2010; Pulz, 2001)
CO2 losses	High	Low	Moderate	(Mata et al., 2010; Pulz, 2001)

Table 2
Space requirement and biomass productivity of various cultivation systems.

Cultivation system	Algae species	Surface area (m^2)	Working volume (L)	Biomass production	Ref.
Shallow pond	*Dunaliella salina; Spirulina*	Several hectares	–	> 1 g/L	(Borowitzka, 1994)
Circular pond	*Chlorella*	500	–	> 1 g/L	(Borowitzka, 1994)
	B. braunii	1.15	40	1.4 g/L	(Ranga Rao et al., 2012)
Raceway pond	*Spirulina; Chlorella; D. salina*	1000	–	> 1 g/L	(Borowitzka, 1994)
	Tetraselmis sp.	12	1000	9 g/m^2/day	(Narala et al., 2016)
	Tetraselmis sp.	20	–	8.37 g/m^2/day	(Chiaramonti et al., 2013)
	Nannochloropsis sp.	20	–	14.1 g/m^2/day	(Chiaramonti et al., 2013)
	Botryococcus bruanii	9.2	2000	1.7 g/L	(Ashokkumar and Rengasamy, 2012)
	Chlorella vulgaris	0.3	–	0.57 g/L/day	(Li et al., 2013)
	Tetraselmis sp.	1	200	36 g/L/day	(Raes et al., 2014)
	B. braunii	0.678	40	1.8 g/L	(Ranga Rao et al., 2012)
	Scenedesmus obliquus	1.93	530	8.26 g/m^2/day	(Arbib, Ruiz, álvarez-Díaz, Garrido-Pérez, Barragan and Perales, 2013)
Flat plate PBR	*Chlorella pyrenoidosa*	0.0375	15	0.67 g/L	(Huang et al., 2014)
	Chlorella sp.	0.5	20	11 g/m^2/day	(Zhang et al., 2013a)
Column PBR	*Chlorella vulgaris*	0.0314	56	0.962 g/L	(Khoo et al., 2016)
	Chlorella vulgaris	0.00196	1.3	0.61 g/L/day	(Aghaalipour et al., 2020)
Annular PBR	*Chlorella vulgaris*	0.08	2	4.24 g/L	(Chang et al., 2016)
	Chlamydomonas reinhardtii	–	6	2.28 g/L	(Loubiere et al., 2011)
Tubular PBR	*Tetraselmis sp.*	4.6	1200	13 g/m^2/day	(Narala et al., 2016)
	Tetraselmis sp.	1.5	40	67 g/L/day	(Raes et al., 2014)
	Phaeodactylum tricornutum	–	–	1.90 g/L/day	(Molina et al., 2001)
	Phaeodactylum tricornutum	1.13	75	1.4 g/L/day	(Hall et al., 2003)
	Scenedesmus obliquus	0.6	380	21.76 g/m^2/day	(Arbib et al., 2013)
	Nannochloropsis gaditana	–	340	15.62 g/m^2/day	(Romero Villegas et al., 2017)
Hybrid system	*Tetraselmis sp.*	16.6	2200	14 g/m^2/day	(Narala et al., 2016)
	Scenedesmus obliquus	0.072	1.5	0.35 kg/m^3/day	(Deprá et al., 2019)
	Algal community with dominance of *Parachlorella sp.*	–	60	20 g /m^2/day	(Yun et al., 2018)
	Staurosira, Desmodesmus	400	–	30.5 g/m^2/day	(Huntley et al., 2015)
	Chlorella homosphaera	1.3	66	3.6 g/L	(Velea et al., 2014)

waters, but also deep-water regions.

Section 2 in this paper presents the features of microalgae cultivation technologies. Recent designs of floating photobioreactors for microalgae cultivation are reviewed in Section 3. Possible combinations of offshore microalgae cultivation technologies are proposed in Section 4 and challenges of establishing offshore cultivation technologies off shore are presented in Section 5. Lastly, Section 6 concludes this review, along with future recommendations.

2. Features of microalgae cultivation systems in floating condition

Besides differentiating microalgae cultivation systems through open and closed systems, cultivation facilities can also be categorized based on the environment of the PBR employment, which are land-based and water-based or floating cultivation systems. There are several major differences between these two cultivating systems, mainly due to the dissimilarities of land and water environment, such as the contrast of cultivation location, existence of significant and continuous external forces, difference in heat capacity of air and water, and distinction between land and water habitats. The contrast between the two environments provides floating cultivation systems with advantages over land-based cultivation systems, for instance, free mixing energy, nutrients, water source, vast space, and temperature control by surrounding water (Kirnev et al., 2020; Zittelli et al., 2013), as summarized in Table 3.

2.1. Reduction of dependence on land

Floating PBRs are designed to cultivate microalgae on the water surface to reduce competition for land and space mainly used for agricultural crops and human development. With reference to an optimistic productivity of 30–50 tonnes per hectare per year (Phang, 2018;

Table 3
Differences between land and floating PBRs.

Parameter	Land-based PBRs	Floating PBRs	Ref.
Surrounding Environment	Air	Water	
Specific heat capacity	700 J/kg K	4200 J/kg K	(Bice, 2008)
Temperature control system	Necessary	Free	(Zhu et al., 2019c; Zittelli et al., 2013)
Dependence on land space	Yes	No	(Zhu et al., 2019c)
External forces	Wind	Wind and Waves	(Zhu et al., 2019c)
Natural external mixing forces	No	Yes	(Zhu et al., 2022)
Mixing methods	Mechanical agitator, Pumps, Aeration	Pumps, Aeration, Water currents, Surface waves	(Zhu et al., 2022)
Structure	Fixed	Floating	(Zhu et al., 2022)
Direct intake of nutrients from surrounding environment	Not possible	Possible	(Zittelli et al., 2013)

Thangavel and Sridevi, 2015) the area of land required to produce 2 % alternative aviation fuel using microalgae biomass in Malaysia is estimated to be 10–18 square kilometres (1000–1800 ha). Such vast land area for production facility may not be economical in urban areas, especially in coastal cities (Trent, 2012). Land-based PBRs require huge land surface to receive sufficient illumination, especially open ponds that are usually designed to be a shallow pond with big surface area, as displayed in Table 2. Commercial open ponds range from 0.15 to 55 ha (Maeda et al., 2018).

Onshore PBRs are subjected to high land cost compared to offshore PBRs. A research conducted by Beal et al. (2015) mentioned that the annual land lease is $6.50 (in United States dollar) per acre per year in Texas, and $15 per acre per year in Hawaii, whereby depending on the size and location of the commercial-scale microalgae cultivation farm, expenditure for land rental will be affected. Offshore ocean space, by contrast, which occupies up to 71 % of the Earth's surface, provides an enormous area for Blue Economy development. Thus, by utilizing offshore open water surface, the cost for land competition in large-scale cultivation and constraint of space on land can be eliminated. Concurrently, microalgae cultivation industry is able to boost economic growth and environmental sustainability of ocean economy.

2.2. External environmental forces

Compared to land-based PBRs which are placed on static foundation, floating PBRs are subjected to significant and continuous external environmental forces, including winds, waves, and currents, therefore it is compulsory to investigate the hydrodynamic motion of the floating structure (Zhu et al., 2019a). Although buoyancy forces and external forces might complicate the estimation of desired structural strength of the PBR, the free external energy can be utilized to mix the microalgae culture (Kim et al., 2016), as shown in Fig. 4(a). External wave forces acting on the structure contribute to sloshing motion of the microalgae culture; significant mixing and providing mass transfer effects due to the kinematics of free surface and flow instabilities (Kim et al., 2017; Said et al., 2017; Song et al., 2013). As displayed in Fig. 4(b) and Fig. 4(c), vortices are formed when sloshing is induced by waves. The dynamics of the vortices are highly related to efficiency of mixing and mass transfer. For instance, Zhu et al. (2017) investigated a plastic bag PBR, where mixing was induced by the rocking motion of a platform, triggered by water motion to actuate the PBR to move in rocking motions similar to natural renewable energy such as waterfalls, wind, or wave. The rocking motion from nature forces was able to exhibit significance results for biomass concentration up to 2.73 g/L.

Utilizing wave energy for mixing in floating PBRs reduces the reliance on electric equipment, such as aeration systems, pumps or motors. The employment of renewable energy, such as wave, wind and hydraulic can lead to reduction on energy consumption and increase the net energy ratio (NERs) for microalgae biofuels production. For instance, the mixing of the culture consumes up to 28 % of the energy input for cultivation (Chisti, 2008a), contributing up to 29.9 % and 52.0 % of the total production cost for tubular PBRs and flat panel PBRs (Norsker et al., 2011). The current net recovery of energy in oil a.k.a. NER for

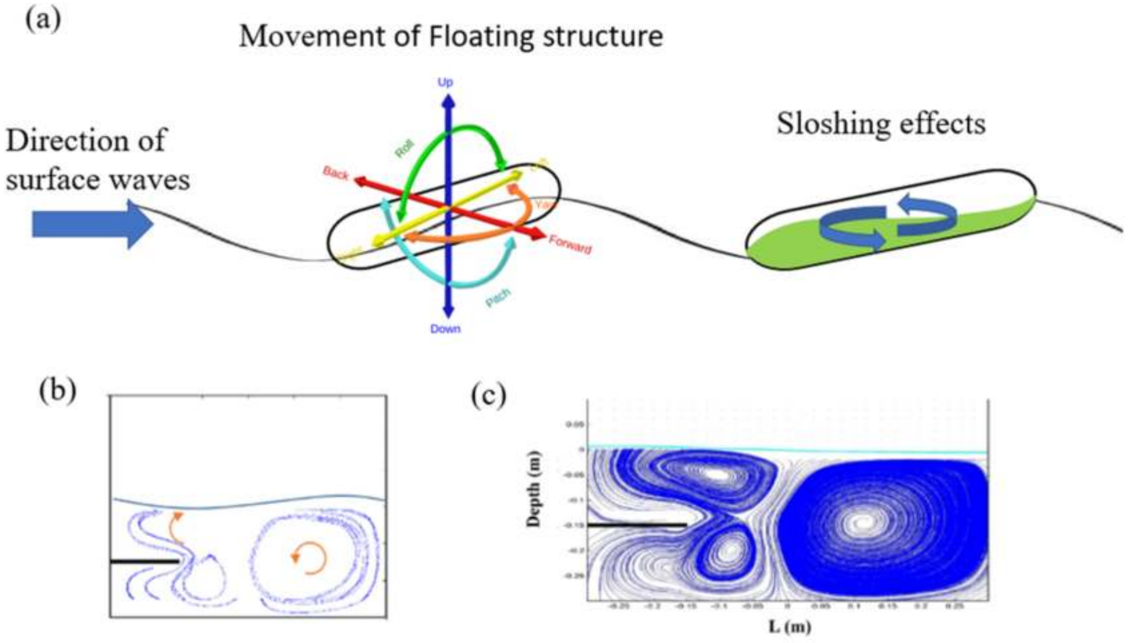


Fig. 4. (a) Concept of wave-induced sloshing; (b) Simulated particle trajectories with wave-induced sloshing in floating baffle tank (Chen, Yang, Wu, Lee and Chen, 2018); (c) Streamline patterns of tank under wave-induced sloshing in floating baffle tank (Chen et al., 2018).

algae biofuel is around 1, whereas the preferred NER value is at least 7 (Chisti, 2013). Therefore, reduction in energy expenditure for mixing is necessary to attain positive progress on development of microalgae biofuel (Rodolfi et al., 2009). Therefore, renewable free energy is a decent solution to reduce energy dependency.

2.3. *Increment in specific heat capacity*

Onshore systems are surrounded by air, thus require additional cooling or heating system to maintain the culture temperature. In contrast, floating systems are immersed in water, which acts as a temperature regulator for the system. Water from the surrounding can be pumped and sprayed on the irradiated surface of a flat panel placed on land to cool down the system, when temperature exceeds the optimum growth temperature for the microalgae species (Huang et al., 2017). Likewise, Willson et al. (2008) immersed a PBR in water to utilize the water environment for temperature regulation. This is possible as water has about four times higher specific heat capacity compared to air. The temperature variation of water surface is less rapid compared to land, thereby continuously immersing floating PBRs in water allows for better sustainment of the culture temperature and omits the need for installation of temperature facilitating equipment.

2.4. *Addition of seawater in cultivation*

By placement in resourceful marine environment, floating PBRs can utilize sea water or fresh water as medium, besides extracting nutrients from the surrounding for microalgae cultivation. Kim et al. (2015) utilized a semi-permeable membrane PBR to transfer nutrients dissolved in seawater into the algae culture. A nutrient gradient is established across the semi-permeable membrane as the nutrients are consumed by the microalgae. However, certain nutrients, such as phosphorus, which are in restricted amount in the surrounding seawater, limit the growth of the algae species. Contrarily, rather than relying on sea water completely for nutrients, Jung et al. (2015) used sea water to replace some key elements in the microalgae culture, such as magnesium, calcium and sodium, which resulted in a more cost-effective cultivation, without sacrificing microalgae growth and biomass production. Ummalyma et al. (2020) cultivated freshwater microalgae using seawater medium, which has advantages such as mineral nutrients, apart from less bacterial and fungal contamination to reduce contamination.

2.5. *Utilization of osmosis technologies for cultivation and harvesting*

Direct contact of floating PBRs with the water environment can also be utilized for cultivation and harvesting process. Kim et al. (2015) utilized a semi-permeable membrane to transfer nutrients dissolved in seawater, which is made possible through the effect of osmosis, while maintaining the pH and salinity of the culture. Forward osmosis, often used to clean wastewater, can be manipulated to capture and reuse nutrients dissolved in wastewater for microalgae cultivation, as displayed in Fig. 5(a). A patent by Trent et al. (2013), demonstrated in Fig. 5(b), besides utilizing exchange membranes for gaseous and nutrient exchange, took advantage of semi-permeable membrane to assist in the harvesting process by dewatering matured culture through forward osmosis to produce a thicker sludge; all of which was aimed to reduce dewatering cost of microalgae biomass.

3. Floating PBR for offshore microalgae cultivation

The concept of floating PBRs could potentially replace conventional cultivation systems, due to more competent productivity of microalgae biomass, and substantially lower cost compared to land-based cultivation systems in terms of capital costs, operational costs and expenditure on maintenance (Dogaris et al., 2015; Huang et al., 2016; Zhu et al., 2014). Some designs make use of transparent polyethylene and recycled polyethylene terephthalate (PET) plastic bottles to reduce the capital cost. Furthermore, the unsettling motion of PBR floating on the water surface due to current and ocean waves provides mixing energy to the cultured medium from ocean renewable source (Zhu et al., 2018b). The offshore cultivation system also benefits from resourceful nutrients (Park et al., 2018; Toyoshima et al., 2015), wide unexploited space (Phang, 2018; Thangavel and Sridevi, 2015), and complimentary temperature regulation.

3.1. *Types of floating PBRs*

One of the earliest studies on floating PBRs was Offshore Membrane Enclosures for Growing Algae (OMEGA) (Wiley et al., 2013), which was a project by the National Aeronautics and Space Administration (NASA) of the United States in 2012, focusing on employing floating PBRs for wastewater and flue gas treatments, as shown in Fig. 6(a). Flexible, clear plastic tubular PBR was employed in coastal areas near coastal cities with sewage discharge and flue gas rich in CO_2 to avoid competition for nutrient with agriculture and disruptions to urban development. The study emphasized on the feasibility of the OMEGA prototype for biofuel production through the usage of wastewater and flue gas as nutrients, besides providing longer life cycle and technoeconomic analyses to provide insights to make the system commercially practical. The experimental trials results showed that the OMEGA system could produce dry biomass of 14 g/m^2/day, with more than 50 % conversion efficiency of supplemental CO_2, and more than 90 % ammonia-nitrogen retrieved from wastewater. However, albeit the revisions of the PBR design, the final Energy Return on Investment (EROI) of the OMEGA

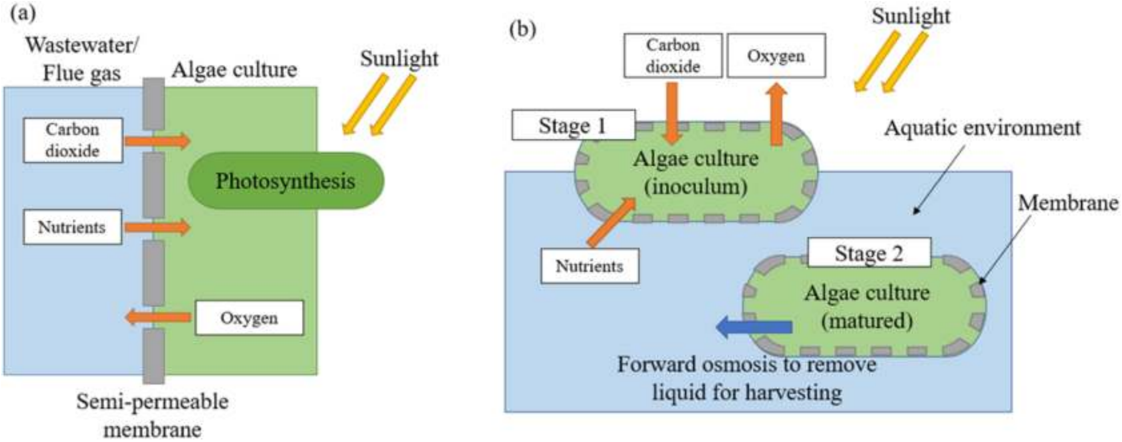


Fig. 5. (a) Nutrient and gas transfer through semi-permeable membrane; (b) Approach of algae bioreactor with semi-permeable membranes (Trent et al., 2013).

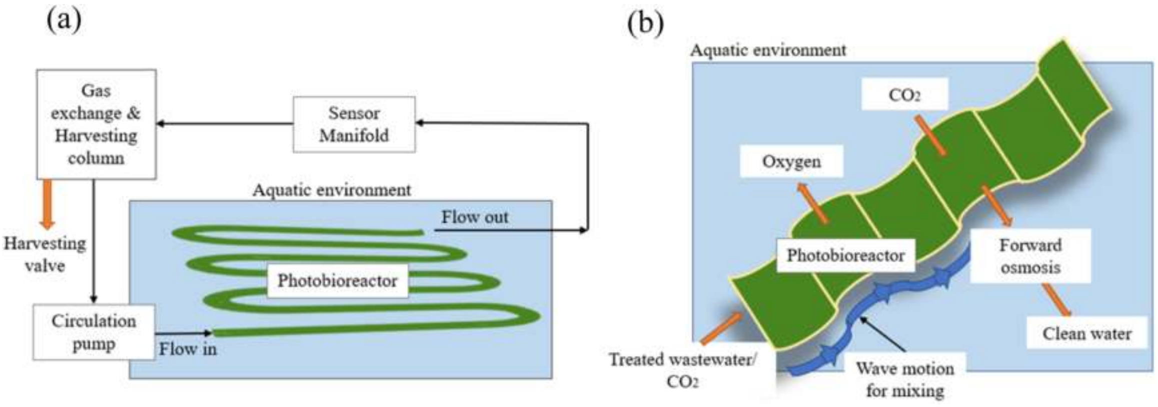


Fig. 6. (a) Schematic diagram of OMEGA (Wiley et al., 2013); (b) Conceptual design of semi-permeable membranes on OMEGA ("OMEGA Project, 2009–, 2012," n.d.).

system is currently less than 3, which makes it impractical to deploy compared to fossil fuels that have an overall EROI of 5–10 (Trent, 2012). There is a need to meet the demands for profitability and environment compatibility, by taking advantages of renewable energy sources and integration with production of profitable by-products for a promising offshore system.

In 2013, Trent et al. (2013) claimed a patent to improve the OMEGA system by attaching semi-permeable membranes on the plastic PBR, as shown in Fig. 6(b). The semi-permeable membranes use the aquatic environment for infrastructural support and temperature regulation. Currents and wave motion provide mixing, while the brackish or marine waters supply the microalgae with nutrients and dewatering actions. The patches of semi-permeable membranes allow beneficial interaction between the contents of the bag and the surroundings, as displayed in Fig. 5(b). When the bag is floating on the water surface, the top membrane allows gas exchange by removing excess oxygen from the bag interior, while allowing entering of CO_2 into the bag, which is essential for algae growth. As the culture matures, it will totally immerse in water. The lower surface of the bag with liquid permeable membrane allows forward osmosis, which removes water from the bag and concentrates the nutrients, aiding in the harvesting and processing process.

Naqquiddin et al. (2014) designed a simple floating PBR made of polyethylene terephthalate (PET) plastic bottle with buoyant material to study mixing variations in the floating PBR, as displayed in Fig. 7(a). Mixing of the microalgae culture in the plastic bottle was varied by manipulating the shape, aeration location, and aeration method, to prevent oxygen buildup while maintaining sufficient mixing effect to boost microalgae growth. Similarly, a pilot scale floating closed culture system was introduced by Toyoshima et al. (2015) to study the possibility of using seawater media as a cheaper culture solution for the growth of *Spirulina Platensis* using floating PBR. Airlift PBRs made of polycarbonate bottles were joined together to form a raft with air floats attached for floatation on the water surface, as illustrated in Fig. 7(b). The intention of using floating PBR was to extend the surface area for microalgae cultivation, compared to open ponds.

A horizontal type PBR that integrates a raceway pond with an airlift PBR, which can be used on both land and water, as shown in Fig. 8(a), was proposed by Dogaris et al. (2015). The PBR was designed to have effective surface area for light exposure while using airlift to ensure sufficient mixing and gas mass transfer. The designed PBR was found economically competitive and had higher productivity than open ponds, as it utilizes low-cost plastic films instead of thick plastic tubes using in common PBRs. This novel PBR also displayed higher productivity compared to open ponds and had lower capital cost compared to common PBRs. Besides, the capital cost for algae biomass production was \$0.42 per kilogram of dry cell weight, which is 2–8 times lower than that of PBRs, comparable to that of open ponds.

A study by Novoveská et al. (2016) focused on optimizing the growth of microalgae culture and sewage treatment by offshore PBRs. Transparent, non-diffusive, durable polyurethane was used to build a tubular module PBR of 45.7 m long and 1.83 m wide with variable depth, as indicated in Fig. 8(b). Openings and gas headspace were created on each tubular module to facilitate the diffusion of gases. Additional passive gas openings were also created to prevent gas buildup inside the tubes. Enclosed floating PBR was selected due to its high CO_2 retention, minimal land usage, elimination of evaporative losses, and utilization of surrounding water body for mixing energy and thermoregulation. By utilizing diverse polyculture, the microalgae culture could remove 75 % and 93 % of total nitrogen and total phosphorus, respectively. The culture also eliminated up to 92 % biological oxygen demand (BOD) from

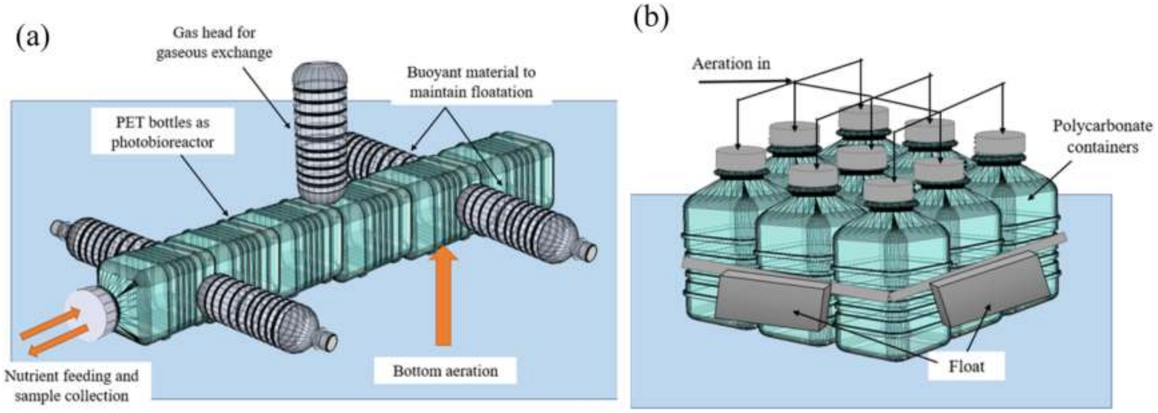


Fig. 7. (a) Floating PET bottles (Naqquiddin et al., 2014); (b) Raft floating PBR (Toyoshima et al., 2015).

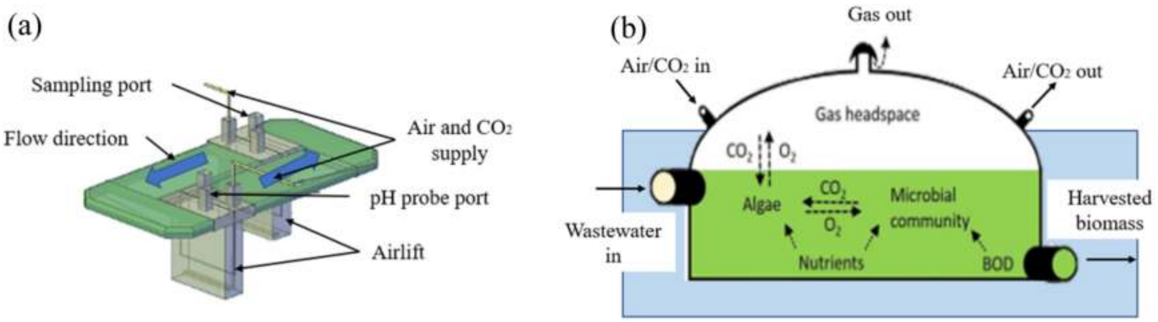


Fig. 8. (a) Combination of raceway pond and airlift (Dogaris et al., 2015); (b) Cross sectional view of tubular module PBR (Novoveská et al., 2016).

sewage. Although there were minor mixing effects supplied from the low average wave height from the northern Mobile bay (Novoveská et al., 2016), mixing was more significant during the physical increment and decrement of liquid from the PBR. When environmental conditions were kept constant while the harvesting frequency was varied, higher biomass accumulation was observed with higher harvesting frequency, as mixing was more induced with the pumping of liquid in and out of the PBR.

Huang et al. (2016) developed a rotating floating PBR that utilized water currents in natural flowing streams, river, and tidal waves. The design is similar to that of paddlewheel with 6 polymethyl methacrylate sheets, as the paddles and 6 barrels filling up the spaces between the paddles, as shown in Fig. 9(a). Aeration was provided from the sides of the barrels. The rotating floating PBR utilized the water current to turn the rotating PBR to provide agitation and promote light distribution across the culture system. When tested in the raceway pond, the paddles were able to achieve an average rotating speed of 3 s per second, and had an illumination surface area of 0.1558 m^2. Powered by natural water currents, the system needs no cost for agitation and temperature control equipment, with even distribution of light in the microalgae culture.

A floating PBR with internal partitions was developed by Kim et al. (2016), with intention to efficiently utilize ocean waves to improve mixing and mass transfer of microalgae culture. The rectangular floating PBR was constructed from low-density polyethylene (LDPE) film, with a gas-in opening at the bottom and a gas-out opening at the top, as seen in Fig. 9(b). Various internal partition arrangements were installed to investigate the relationship between internal partition of the floating PBR with mixing and mass transfer of the algae culture. The installation of internal partitions was aimed for better mixing of algae culture by keeping cells suspended, besides even light distribution and minimizing settling and clumping of cells at dead spots. Although experimental results showed that the partitioned floating PBR of 2 litres working volume produced higher biomass productivity compared to flat plate PBR, the internal partitions needed further modification when scaled up to 15 litres working volume, implying the difficulties in scalability.

Zhu et al. (2018c) investigated a low-cost floating PBR made of acrylic which utilizes wave energy for mixing and bicarbonate for carbon supply, as shown in Fig. 9(c). The idea was to save energy cost and avoid the high cost of carbon dioxide pipeline on the ocean. By resorting to bicarbonate as the carbon supply for the floating PBR, also named as, bicarbonate-based integrated carbon capture and algae production system (BICCAPS), the proposed system is able to reduce high cost for carbon dioxide capture and transport. The cultivation of *Euhalothece sp.* was able to achieve a final biomass concentration of 0.91 and 1.47 g/L

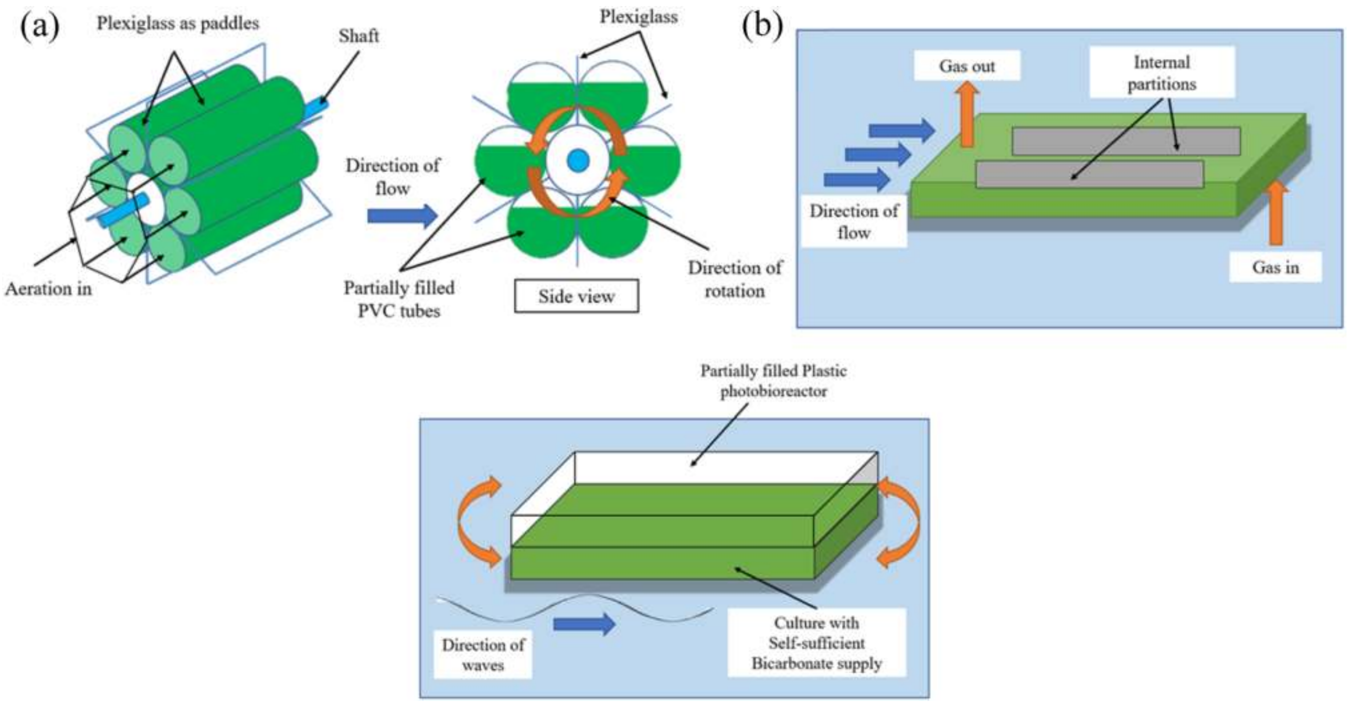


Fig. 9. (a) Rotating PBR (Huang et al., 2016); (b) Rectangular floating PBR with internal partitions (Kim et al., 2016); (c) Simple plastic PBR without aeration (Zhu et al., 2018c).

for indoor and outdoor cultures, respectively. However, as aeration was not provided, the culture faced issues of high dissolved oxygen.

BICCAPS was then used to study the large-scale cultivation of *Spirulina*, where Spirulina was not affected by the high levels of accumulated dissolved oxygen (Zhu et al., 2018b). The scaled up floating PBR (100 L) was able to achieve almost similar biomass concentration and higher apparent carbon utilization efficiency compared to a 10 L culture. The employment of bicarbonate for the floating PBR is crucial for the development and scaling-up of the PBR (Zhu et al., 2022). The bicarbonate supply as the carbon source simplifies the design of the PBR as carbon dioxide capture and transport is no longer needed, while the need for an aeration device is also removed. Meanwhile, mixing is achieved by using wave energy and no electrical equipment is needed.

The hydrodynamic performance of BICAPPS floating PBR in wave conditions was investigated by Zhu et al. (2019a, 2019b, 2019c). As the mixing of floating PBR depends on the hydrodynamic movement of the floating structure with regards to the wave conditions, the hydrodynamic performance of the floating PBR was studied. Floating PBRs with different shapes were tested, where the square-shaped PBR encountered more severe motions compared to the rectangular PBR. The movements became more sever with increasing wave frequency and wave height. The culture depth also affected the movement of the floating structure. The study also addressed the relationship between hydrodynamic movement and mooring-line forces, where the mooring system with floaters significantly reduced mooing forces. However, there was limitation in this study, as the wave and liquid interactions were not addressed in detail.

Table 4 summarizes the types of floating PBRs. Floating PBRs are developed with designs aimed for low-cost fabrication material and utilization of nature forces for mixing, to minimize their capital and operational cost (Zhu et al., 2019c). Although mixing of microalgae culture in floating PBRs by wave motions has been studied, the effects of external motion induced mixing are generally determined based on the productivity of the microalgae culture (Kim et al., 2016), while the integration between the structure motion in waves which affects the sloshing motion in the microalgae cultures has not been studied. From the comparison of previous researches on floating PBRs, there is still a lack of studies on the dynamics of floating structure, flow effect on the microalgae culture due to external motions, effect of varying wave conditions on the mixing of culture (Zhu et al., 2019c), variation in floating PBR shape and geometry, as well as the construction and installation of floating PBRs in offshore environment. These indicate the need to integrate phycology studies with marine engineering to further develop floating PBRs.

3.2. *Differences between floating PBRs of various water bodies*

Floating PBRs can be employed on any surface of water bodies, such as ocean, flowing water and lakes. Each of these water bodies have different characteristics, such as salt or fresh water, large or small, and flowing or contained. Each water body has its own features depending on its geographical features. For instance, oceans and seas are bodies of salt water that holds almost 96.5 % of the Earth's water (Shiklomanov, 1993). From the remaining water bodies, only about 0.01 % are lakes and rivers. Oceans, seas and bays take up to 68.5 % of the Earth's surface but more than 80 % of the ocean remained unexplored (Ocean, 2021). Therefore, the ocean has more unused surfaces that can be exploited compared to other water bodies.

From the perspective of utilizing renewable energy, employment of floating PBRs in different water bodies also has different potential sources of renewable energy. For instance, by employing the floating PBR to the ocean, renewable energy sources that can be utilized include, wave energy, ocean current energy, ocean thermal energy conversion, salinity gradient energy, and tidal energy (Neill, 2022). In contrast, river has more limited renewable energy sources, mainly hydropower, which is created by the falling or fast running water (Kuriqi et al., 2021), whereas, other inland contained water bodies, such lakes and ponds may not have sufficient water motion that can be utilized for mixing.

Different locations might also limit the availability of resources. Depending on the location, if the floating PBR is installed nearby to offshore facilities that are located at deep sea. Resources need to be transported from land facilities. The BICCAPS proposed by Zhu et al.

Table 4
Types of floating PBRs.

Photobioreactor (PBR)	Mixing method	CO_2 source	Material	Purpose of research	Species	Size	Production	Ref.
OMEGA	Mechanical pump	Gas	polyethylene	Wastewater and flue gas treatment	Domination of *Desmodesmus sp.*	110 L	14.1 $g/m^2/day$	(Wiley et al., 2013)
Tubular modular tubes with gas head	Aeration	Gas	polyurethane	Wastewater treatment Optimization of cultivation system	Domination of *Chlorella*, *Cryptomonas* and *Scenedesmus.*	0.5 acres	3.5–22.7 $g/m^2/day$	(Novoveská et al., 2016)
Plastic bottle PBR	Aeration	Gas	PET bottles	Optimization of aeration system	*Spirulina*	20 L	0.090 g/L/day	(Naqquiddin et al., 2014)
polyethylene culture containers	Aeration	Gas	polypropene or polycarbonate	Investigation of closed floating system	*Spirulina*	20 L	9 $g/m^2/day$	(Toyoshima et al., 2015)
Hybrid PBR	Aeration	Gas	polyethylene	Novel design of hybrid floating PBR	*Nannochloris atomus*	65 L	12.9–18.2 $g/m^2/day$	(Dogaris et al., 2015)
Tubular module PBR	Mechanical pump	Gas	–	Saline medium	*Tetraselmis sp.*	50 & 2500 L	0.03 g/L/day	(Park et al., 2018)
Partitioned PBR	Aeration Water waves	Gas	polyethylene	Mixing method	*Tetraselmis sp.*	2 L	–	(Kim et al., 2016)
Rotating floating PBR	Continuous water flow	Bicarbonate	PET bottles	Novel design of rotating floating PBR	*Dunaliella tertiolecta*	18 L	3.10 $g/m^2/day$	(Huang et al., 2016)
Plastic bag PBR	Water waves	Bicarbonate	Acryline	Mixing method	*Euhalothece sp.*	1.4 L	17.06 $g/m^2/day$	(Zhu et al., 2017)
Plastic bag PBR	Water waves	Bicarbonate	PVC membrane	Scale up issues	Spirulina platensis	100 & 1000 L	18.9 $g/m^2/day$	(Zhu et al., 2018b)
Plastic bag PBR	Water waves	Bicarbonate	–	Cost reduction	*Euhalothece sp.*	100 L	8.27 $g/m^2/day$	(Zhu et al., 2018c)
Plastic bag PBR	Water waves	Bicarbonate	–	Effects of wave on structure motion	–	–	–	(Zhu et al., 2019a)

(2018c) includes a suggestion on the transport of microalgae culture. The cultivation of microalgae inside the floating PBR is conducted with bicarbonate-based medium and towed to desired location. When the culture is ready for harvest, the algae broth is transported back to the land-based facility. Besides, floating PBRs can be located near coastal areas are still close-by to resources. For instance, the employment of OMEGA which was planned to be installed at coastal areas to be near to wastewater sources and assist in the wastewater treatment of coastal cities (Wiley et al., 2013). Other fresh water bodies, such as rivers and ponds, that are located in-land are closer to resources compared to deep sea offshore facilities.

Although further from resources, compared to inland water bodies, the employment of floating PBRs to the ocean surface allow more opportunities to cooperate with blue economics. For instance, the floating PBRs installed nearby offshore facilities are able to aid with wastewater treatment and carbon dioxide sequestration (Novoveská et al., 2016; Zhu et al., 2021). Besides, the floating PBR is able to produce valuable by-products to add value for the blue economics. In terms of aquaculture, biomass produced from floating PBRs can be directly used as aquaculture feed. More opportunities of floating PBRs with blue economics is mentioned in detail in Section 4.0.

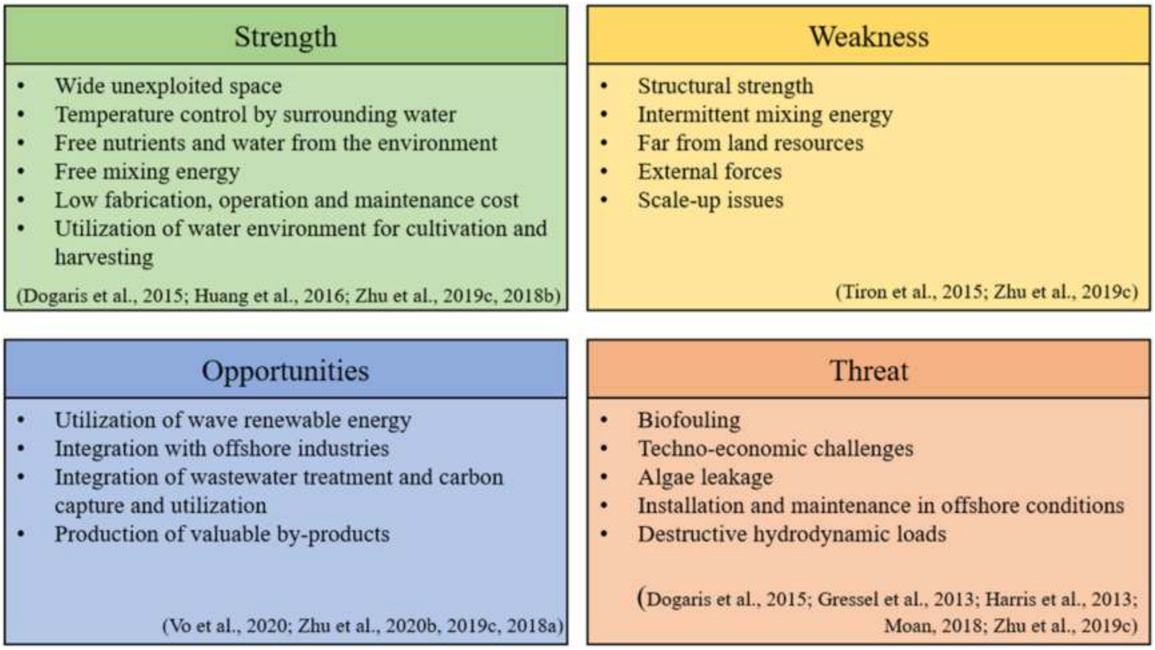
In terms of structural design, ocean structures require more robust structural design, as they are often subjected to destructive forces during hurricanes and bad weathers, such as slamming effects (Zhang et al., 2021). In contrast, structures placed at the river or other inland water bodies are close by to other land structures. These structures have less demand on structural issues, as they can be sheltered by nearby land structures. A SWOT analysis is shown in Fig. 10 to briefly display the strength, weakness, challenges and opportunities of offshore floating PBRs.

3.3. *Design parameters of floating PBRs*

Biomass production of microalgae requires light, water, CO_2 and nutrients. Akin to terrestrial plants, most microalgae species can conduct photosynthesis to convert CO_2 to oxygen by utilizing light energy. Generally, for microalgae biomass productions, the main parameters of concern are: (i) light intensity and distribution; (ii) concentration of dissolved CO_2 and dissolved oxygen; (iii) amount of major and minor nutrients; (iv) temperature; and (v) pH (Chisti, 2008b). According to Grobbelaar (2000), major parameters for manipulation of mass algae cultures include: (i) culture depth or optical cross section that affects the penetration of light; (ii) turbulence to mix the culture; (iii) nutrient content and supply, including CO_2 exchange; (iv) cultivation method; (v) areal density and biomass concentration; and (vi) photosynthetic potential of the system, as illustrated in Fig. 11. To ensure maximum productivities of algae culture systems, the main principles are: (i) adequate mixing; (ii) high volumetric mass-transfer; (iii) high surface-to-volume ratio; (iv) optimized temperature control; (v) optimized pH control, gas supply and sufficient nutrients; (vi) appropriate harvesting regime; and (vii) adequate inclination to maximize photosynthetic efficiency (Posten, 2009; Tredici, 2010).

Besides manipulating the growth and environmental parameters during the design of PBRs, the scalability of the cultivation system also requires crucial consideration (Pruvost, 2011). In fact, floating PBRs also face difficulties in scaling up. Typically, large scale cultivation of microalgae faces two main bottlenecks, which is high cost and low efficiency (Zhang et al., 2016). High cost is due to the high consumption of resources, such as energy, land, water and nutrients. Meanwhile, low efficiency is the low productivity of biomass at large scale due to non-optimized utilization of resources. Most currently available PBRs have limited scalability as the higher the production volume, the more challenging to manipulate the growth and environmental parameters for the growth of microalgae, therefore, often leading to decrease in biomass production and performance when scaled up (Acién et al., 2017; Zittelli et al., 2013). For example, the vertical column PBR has shading effect issues on large scale, while the horizontal tubular PBR requires large space and has dissolve oxygen build up issues (Gupta and Choi, 2015).

In short, design parameters usually discussed in the design of PBRs typically involve growth parameters, and environmental parameters, besides scalability, cultivation and harvesting methods. Growth parameters include light intensity and distribution, nutrient content, CO_2 supply, pH, and temperature, whereas environmental parameters comprise of mixing and aeration parameters. In this review, the effect of mixing parameters utilizing external forces will be further discussed. Other additional considerations for floating PBRs, such as location selection, algae selection and hydrodynamic loads are also discussed.



Strength

- Wide unexploited space
- Temperature control by surrounding water
- Free nutrients and water from the environment
- Free mixing energy
- Low fabrication, operation and maintenance cost
- Utilization of water environment for cultivation and harvesting

(Dogaris et al., 2015; Huang et al., 2016; Zhu et al., 2019c, 2018b)

Weakness

- Structural strength
- Intermittent mixing energy
- Far from land resources
- External forces
- Scale-up issues

(Tiron et al., 2015; Zhu et al., 2019c)

Opportunities

- Utilization of wave renewable energy
- Integration with offshore industries
- Integration of wastewater treatment and carbon capture and utilization
- Production of valuable by-products

(Vo et al., 2020; Zhu et al., 2020b, 2019c, 2018a)

Threat

- Biofouling
- Techno-economic challenges
- Algae leakage
- Installation and maintenance in offshore conditions
- Destructive hydrodynamic loads

(Dogaris et al., 2015; Gressel et al., 2013; Harris et al., 2013; Moan, 2018; Zhu et al., 2019c)

Fig. 10. SWOT analysis of offshore floating PBRs.

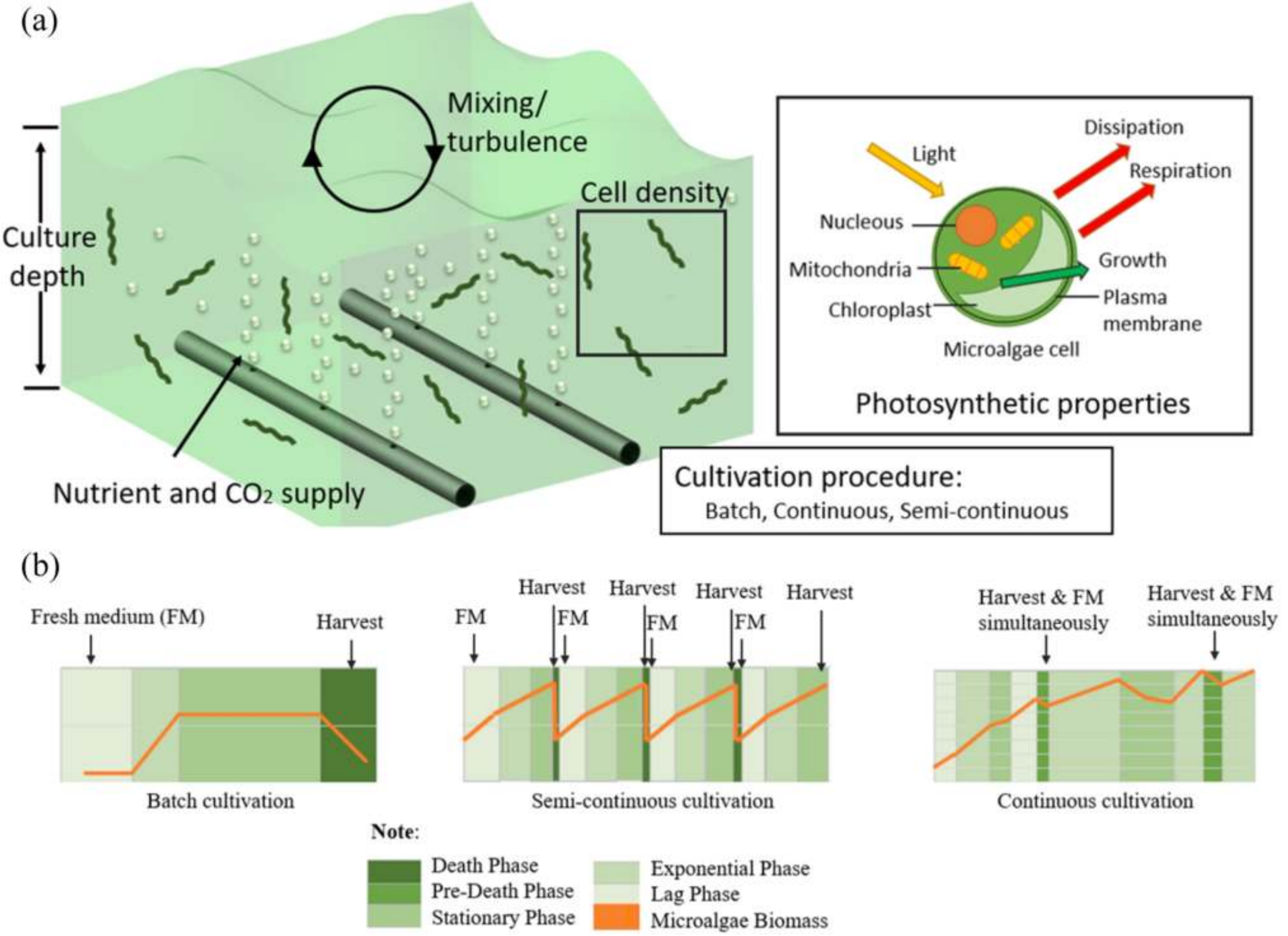


Fig. 11. (a) Major parameters for handling mass microalgae cultures (Grobbelaar, 2000; Vale et al., 2020); (b) Growth pattern of different cultivation procedure (Peter et al., 2022).

3.3.1. *Mixing parameters*

Mixing is an important parameter in the cultivation of microalgae (Cicci et al., 2015; Guo et al., 2015), as it is essential for the distribution of nutrients, pH, temperature, dissolved CO_2 in more uniform flows of the culture broth (Anjos, Fernandes, Vicente, Teixeira and Dragone, 2013). It also effectively prevents cell sedimentation, cell clumping, cell attachment to the walls of the PBR, and emergence of dead zones (Huang et al., 2017), providing even dispersion of cells, heat and gas transfer across gas-liquid boundary (Eriksen, 2008). Furthermore, mixing enhances the redistribution of light intensity (Huang et al., 2017; Wang et al., 2012) where the beneficial light/dark cycles can promote the growth of photosynthetic microalgae (Takache et al., 2015).

Table 5 summarizes the studies that focused on improving mass transfer and mixing to enhance microalgae growth in various types of PBRs. Common methods to improve mixing include the additions of mixers or internal partitions or baffles, optimization of aeration for bubble and airlift columns, and optimization of PBR geometry. Most of the methods still rely on an external mechanical pump or aeration system to attain uniform mixing in the culture. For example, Zhang et al. (2013a, 2013b) studied the hydrodynamic characteristics of a tubular PBR installed with static helical mixers, concentrating on the flow dynamics, swirl number, cell trajectories, and energy consumption of the modified PBR. The use of helical static mixers resulted in 37.26 % increase in biomass productivity, as the helical mixers produced swirling flow in the PBR. However, the manipulation of the geometry of static mixer and inlet velocity also resulted in higher energy consumption.

Other researches on the effects of mixing by the addition of internal mixers also resulted in higher biomass productivity; for example, up to 90 % increase in biomass concentration was observed by Huang et al. (2014), who applied different arrangements of internal agitators in a bubbling flat plate PBR, such as split airlift reactor and central airlift reactor. The central flat-plate PBR with airlift reactor was able to produce a fluid flow similar to plug flow, compared to flat plate PBR with split airlift reactor that has a more irregular and radial fluid flow. Therefore, for the flat plate PBR with central airlift reactor, the installation of internal mixers in the flat plate PBR successfully enhanced the periodicity of the light-dark cycles and enhanced the liquid motion along the light gradient.

Guo et al. (2015) investigated on the optimization of aeration and mass transfer in a rectangular airlift loop PBR. The influence of superficial gas velocity on the top clearance of reactor was discussed in detail, besides analysis on the effects of superficial gas velocity on the cultivation of algae. The study on the relationship between the impact of top clearance of reactor showed that circulation velocity rose with the expansion of top clearance, displaying the influence of geometry of the reactor on mixing efficiency. Modification of top clearance resulted in almost 125 % magnification of circulation velocity. Apart from that, the researchers analysed the effects of superficial gas velocity on the cultivation of algae, where the enhancement of superficial gas velocity produced satisfying results of the light-dark cycles; however, harmful shear stress might have been developed and harm the algae strains. The optimum superficial gas velocity analysed from this study for *Chlorella*

Table 5
Parameters studied on the effect of mixing on microalgae growth.

Cultivation system (PBR)	Algae species	Installation to improve mixing	Biomass			Rate of aeration (vvm)	Mixing time	Mass transfer coef.	Fluid velocity along light gradient (m/s)	Light/Dark cycle		Ref.
			Conc. (g/L)	Productivity (g/L/day)	% Increase in biomass					Freq. of LD cycle (Hz)	Light time ratio	
Tubular	*Chlorella sp.*	Helical static mixers	1.75	0.175	37.26	–	–	–	–	0.88~3.23	–	(Zhang et al., 2013a)
Flat plate	*Chlorella sp.*	Inclined baffles	–	14.29 g/m^2/day	29.94	–	–	–	–	4–10	–	(Zhang et al., 2013a)
Flat plate	*Chlorella pyernoidosa*	Special mixers	1.3	–	31.90	1	10–50 s	–	0.05~0.08	0.28~0.53	–	(Huang et al., 2014)
Floating plastic	*Tetraselmis sp.*	Internal partitions	–	0.12–0.47	32–50	0.2	70 % higher	0.085~0.188 /min	–	–	–	(Kim et al., 2016)
Tubular	*Chlorella sorokiniana*	Internal static mixers	–	0.43–1.47	15–70	0.125~1.250	100~300 s	0.14~0.35 /min	–	–	–	(Ugwu et al., 2002)
Tubular	*Chlorella sp.*	Internal baffle	3.52	0.587	40	0.06	–	–	–	–	–	(Ryu et al., 2009)
Column	*Chlorella sp.*	Bubble driven internal mixer	8.6	1.4	33	1.0–1.5	–	–	–	–	–	(Naira et al., 2020)
Tubular	–	Static mixers	–	–	–	–	–	–	–	1.4	–	(Gómez-Pérez et al., 2020)
Tubular	–	Inner tube	–	–	–	0.07	–	–	–	1.01–1.8	–	(Cui et al., 2020)
Flat plate	*Chlorella vulgaris*	Double paddle wheels	1.543	–	62.30	0.02~0.10	–	–	0.12~0.27	0.035~0.131	31.8 % increase	(Xu et al., 2020)
Plate	*Chlorella sp.*	Jet-aerated tangential swirling-flow plate	1.45	0.29	46.50	–	–	–	–	0.13	33.4 % increase	(Cheng et al., 2020)
Plate	*Chlorella sp.*	Jet-aerated tangential swirling-flow plate	1.33	–	49.40	0.06	32.07 s	48.9 /hour	–	–	–	(Cheng et al., 2019)
Column	*Chlorella vulgaris*	Inclined mixers	2.1	–	–	1.0–1.5	–	–	0.05~0.32	–	–	(Azizi et al., 2018)
Flat plate	*Chlorella pyernoidosa*	Inner structures	–	0.432	–	0.2	–	–	0.022	0.27~0.38	–	(Huang et al., 2015b)
Flat plate	*Chlorella pyrenoidosa*	Internal mixers	0.89	0.264	–	0.6	–	–	–	0.31~0.49	–	(Huang et al., 2015a)

vulgaris was 8.333×10^{-4} m/s.

Gao et al. (2018) conducted a simulation and predicted the consequences of mixing and shear stress in an airlift PBR on the microalgae growth. Mixing induced by bubbling can increase the biomass production but in excess, might also cause the increase of local shear stresses that can impede biomass production. Simulation results with inclusion of shear stress resulted in better compatibility with the experimental results. When shear stress was not included for the case of perfect mixing, the superficial gas velocity of 0.82 cm/s had the best dry biomass concentration. However, when shear stress was included, the optimum superficial gas velocity was only 0.16 cm/s. Thereby the simulation results indicated that higher gas flow rates had suppressed biomass accumulation due to shear stress induced in the culture.

Table 6 presents the influence of the hydrodynamics on the productivity of microalgae culture. Generally, addition and optimization of mixing technologies area will increase the biomass production; however, the extent of the effect is still unclear. Addition of internal baffles can improve the fluid flow properties, thereby enhancing the effects of mixing, mass transfer and light-dark cycles to boost the microalgae growth. Although various researches had been conducted to investigate the effect of mixing on microalgae productivity, direct comparison between researches conducted is not feasible due to differences in control parameters, such as type of PBR, geometry of PBR, location, light intensity, nutrient contents, and microalgae species. The current state-of-art measurement of the algae industry is not well-developed, and there is no standard descriptive language nor specific measurement methodology, thus it is difficult to harmonize the data inputs towards a more uniform description and testing of algae biomass and products (Laurens et al., 2015).

Nonetheless, by ranging down and focusing on certain parameters, such as the optimum air or liquid flow rate and a specific algae species from previous studies, as shown in Table 6, the optimum liquid bulk velocity flow rate for raceway ponds for *Spirulina Platensis* was found in the range of 10–30 cm/s (Becker, 1994), while the optimum liquid bulk velocity flow rate for raceway ponds for *Chlorella sp.* was in the range of 10 cm/s to 50 cm/s (Weissman et al., 1988). Depending on the microalgae species, the range of optimum flow velocity varies, thus emphasizing the need for specific study on different mixing methods on the designated microalgae species. Different microalgae species have varying susceptibility to shear stress developed due to mixing and other controlled growth parameters, thereby the productivity obtained in different studies also differs greatly.

3.3.2. Location selection in deployment of floating PBRs

Location selection for microalgae cultivation must consider the availability of nutrients and suitable growth parameters for the selected microalgae species, for example, organic and/or inorganic carbon, major and minor nutrients, light intensity, and optimum temperature range. Similar for both onshore and offshore microalgae cultivation facilities, locations in different climate regions yield varying productivity, as displayed in Fig. 11. As presented by Franz et al. (2012), maximum annual yields are dependent on the solar irradiance and temperature patterns of the locations. As shown in Fig. 12(a), the location of high lipid productivity for biofuel is at the equator, in regions that have annual average temperature of 15 degrees or higher, as illustrated in Fig. 12(b). In terms of nutrient availability, the selection of offshore areas nearby coastal cities is particularly to ensure availability of flue gas and wastewater as sources of nutrients for microalgae cultivation (Wiley et al., 2013). As the designated system is to perform wastewater treatment and CO_2 utilization, research facilities nearby coastal cities do not require expenses for the construction of long pipelines and operational cost of pumping wastewater for long distances.

Energy sources should also be considered during location selection for the installation of microalgae cultivation facilities. Different locations have different electricity tariffs, which will eventually affect the production cost of the microalgae biomass. Electrical consumption

Table 6
Optimum gas or liquid velocity flow rate for microalgae growth.

Algae Species	PBR	Mixing mode	Size	Environment *	Mixing velocity (m/s)	Aeration flow rate (vvm)	Algae productivity	Ref.
Spirulina platensis	Inclined flat panel	Bubble column	70 cm thick 90 cm long 2.6 cmwidth	U		2.5	2.2 $gL^{-1}d^{-1}$	(Hu et al., 1996)
	Floating PBR	External agitation by waves	1000 L	U			6.63 $gL^{-1}d^{-1}$	(Zhu et al., 2018b)
	Flat plate	Airlift	–	C		4	110 $mgL^{-1}hr^{-1}$	(Qiang and Richmond, 1996)
	Raceway pond	Paddle wheel	–	–	0.1–0.3			(Becker, 1994)
	Flat panel	Airlift	50 L	C		0.046	30.57 % CO_2 utilization efficiency	(Reyna-Velarde et al., 2010)
Chlorella sp.	Raceway pond	Paddle wheel	100 m^2	–	0.1–0.5			(Benemann et al., 1987)
Chlorella vulgaris	Tubular	Airlift	20 L	C		0.1755	80 % CO_2 removal efficiency	(Sadeghizadeh et al., 2017)
	Tubular	Bubble column	30 L	C		0.10–0.15		(Bitog et al., 2014)
	Column	Bubble column	56 L	C		0.16	1.05 g/L	(Khoo et al., 2016)
	Flat plate	Airlift	0.05 m × 1 m × 1 m	C		0.035	39.6 g/L	(Guo et al., 2015)
Chlorella mutant PY-ZU1	Tubular	Bubble column	⌀2.5 cm, 100 cm length	C		0.3	Growth rate of 5.5 g/L	(Cheng et al., 2019b)
S. obliquus	Hybrid of flat plate and bubble	Bubble column	Area = 720 cm^2	C			2.8 kg/m^3	(Deprá et al., 2019)
C. reinhardtii	Torus shape	Impeller	1.3 L	C	0.05		–	(Pruvost et al., 2006)
Chlorella sp. AG10002	Tubular	Bubble column	600 ml	C		0.02	2.58 ~ 3.52 g/L	(Ryu et al., 2009)
S. aquatilis SI-2	Flat plate	Bubble column	3–9 L	C		0.005	0.13 $gL^{-1}hr^{-1}$	(Zhang et al., 2002)

* U for uncontrolled environment (outdoor cultivation), C for controlled environment (indoor or lab cultivation)

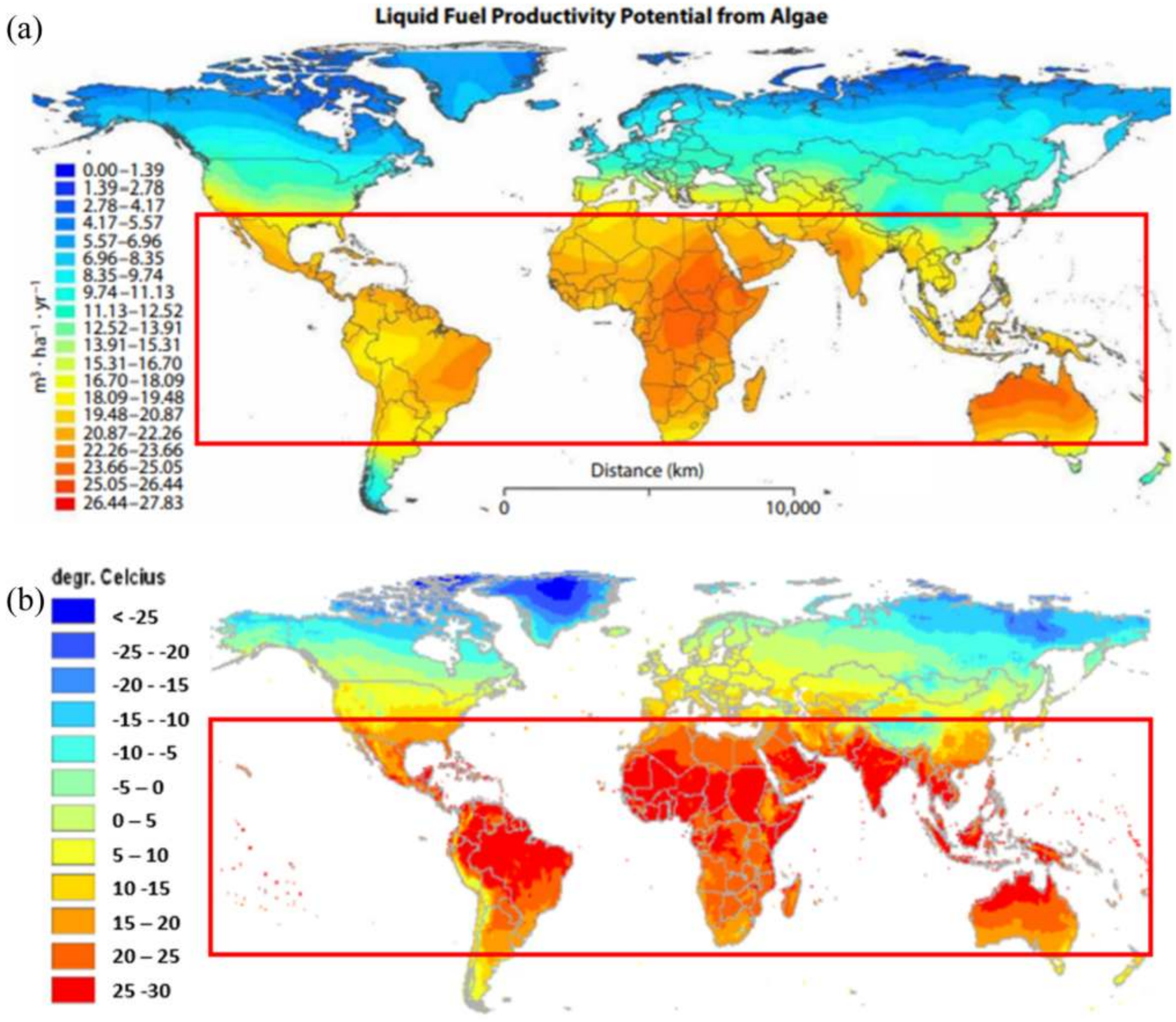


Fig. 12. (a) Map of relative liquid fuel productivity potential from microalgae (Greene et al., 2016; Moody et al., 2014); (b) Temperature suitable for microalgae cultivation (Hadiyanto and Kumoro, 2012). *Red box indicating location of high microalgae productivity.

contributes up to half of the total cost for energy and materials. For example, considering cases without renewable energy, the electricity tariff is \$0.31/kWh in Hawaii, while the electricity tariff in Texas is \$0.06/kWh (Beal et al., 2015). The difference between the electrical tariffs means the total cost of power in Texas is a third of that in Hawaii. Thereby, the material and energy costs in Texas shall be only about 37 ~ 46 % of those in Hawaii. This huge difference in energy cost causes drastic variations to the economic analysis of biomass production, in particular, the net annual revenue, and the return period for investments.

Environmental parameters at different locations also affect the biomass productivity in microalgae mass cultivation (Chew et al., 2018; Wang and Lan, 2018), which include cell distribution, optimal distribution of nutrients and gas, enhancement of light distribution, and maintaining uniform temperature (Grobbelaar, 2000; Posten, 2009; Tredici, 2010). Location selection can also be based on the desired environmental effects of open waters. Floating PBRs mainly aim to utilize the surrounding water movement as mixing energy, as shown by Huang et al. (2016) and Kim et al. (2016) in their researches, where the floating PBRs utilize coastal waves and water current, respectively, as mixing energy to mix the microalgae culture. By selecting locations with suitable waves or water current, the system can be naturally agitated to keep the cell suspended and ensure homogenous light distribution in the microalgae cultivation medium.

Varying locations have different water currents and surface wave characteristics. Characteristics of ocean surface waves depend on various factors, such as tidal waves due to response to gravity, local meteorology, and topography (Laing et al., 1998). Wave characteristics are affected by local meteorology such as the monsoon season, where significant wave height can increase up to three-fold during the monsoon season at central west coast of India, besides having larger variations of peak wave period and significant wave height (Amrutha, Sanil Kumar, Sharma, Singh, Gowthaman and Kankara, 2015). As the ocean modelling community has been emphasizing the coastline, concern on coastal hazards has been rising (Spalding et al., 2014) such as, rising water levels and storm surges. The likelihood and severity of extreme events, such as Hurricanes Katrina and Rita should also be considered. Characteristics of ocean surface waves and local sea current will affect the dynamic response of the floating structure, which correlates with structural safety that should not be unforeseen.

In terms of topography, different water locations and conditions, such as rivers, coastal waters and deep ocean conditions will also have differing effects on the growth of microalgae culture and structural strength. Characteristics of surface waves differ based on the depth of the sea. For example, at shallow water regions, wave length of waves become longer. For coastline areas, although waves are less violent, there are physical processes within the shallow water regions due to long waves, such as shoaling, depth induced breaking, and bottom friction (Shemdin et al., 1978). It is important to conduct accurate assessment of the coastal hydrodynamic models, such as the quality and resolution of the sea-bed representation. Similarly, the strength and severity of waves in deep sea regions should be examined.

Solovyev et al. (2021) explored potential locations for the installation of large-scale floating PBRs at the coastal region of the Black Sea. The study was conducted for one year to observe the meteorological and hydrophysical parameters of the selected locations. The measured data included initial understanding of the Bathymetry data, monthly average wind speed, maximum wind speed, annual distribution of sea wave directions, and wave height of storm situations. Measurements were collected to study the frequency spectra of wind waves at diverse wind action durations to observe the long waves. The main concern was to determine the divergence zones of waves developed from the refraction of waves to pinpoint storm hazards. Through the monitoring, the most suitable location was selected based on calculation results that could ensure most stability with minor damage to the operating facility.

Another challenge affecting the location selection of offshore microalgae cultivation is the integration with other industries; either to achieve a more economical offshore microalgae cultivation industry, or to complement the other industries by producing valuable by-products and provide environmental benefits. As mentioned by Trent (2012) in project report of OMEGA, the EROI of the production of biofuel from the OMEGA system is still inadequate to compete with fossil fuels, thus needs to incorporate with profitable industries. Therefore, to integrate floating microalgae cultivation with other existing offshore industries, floating cultivation locations are best to be placed nearby industries to act as supporting technology. Depending on the location of the offshore industry, modifications are needed to complement the integration, such as the desired function of the culture, size, and availability of energy and nutrient, besides anticipating the weather and wave conditions.

3.3.3. Algae selection in offshore cultivation

Selection of microalgae species relies on the desired application (e.g., CO_2 mitigation, wastewater treatment), biomass application (e.g., biofuel, biogas, biohydrogen), and valuable products (e.g., pharmaceutical compounds, lipids, proteins, vitamins). For instance, the scanning and selection of microalgae species for biological CO_2 utilization are performed nearby power station to shortlist microalgae species that can survive under the conditions of flue gas utilization, such as elevated temperature and high CO_2 concentrations (Chik et al., 2012). Selection of microalgae species can also include identification of valuable by-products, such as lipid enriched microalgae for biodiesel production (Nirmala and S, 2020), for instance, the selection process of microalgae species for biofuel production from dairy effluent, as illustrated in Fig. 13.

Taking into account ocean culture systems, Park et al. (2018) selected *Tetraselmis sp.* after studying various literature regarding the versality of outdoor cultivation with minimal contamination. The main purpose of the selection was to select a microalgae species suitable for large-scale ocean cultivation using hypersalinity to reduce contamination. Since laboratory methods of disinfection and sanitization are not practical for large-scale cultivations, it is necessary for handling culture conditions to minimize the risk of contamination. As the PBR floats in the ocean, although addition of chemicals, filtration, heating or sonification would be immensely more difficult compared to land-based cultivation systems, exploitation of extreme conditions, however, would be much simpler, where the microalgae species is cultivated under hypersaline media to prevent contamination.

It is important to select microalgae species based on the sought-after application, as shown in Table 7. For example, in selecting microalgae species for CO_2 utilization, the selection criteria include CO_2 assimilation ability, high CO_2 tolerance, endurance of trace elements in flue gas, high temperature tolerance, marine or freshwater algae, and light

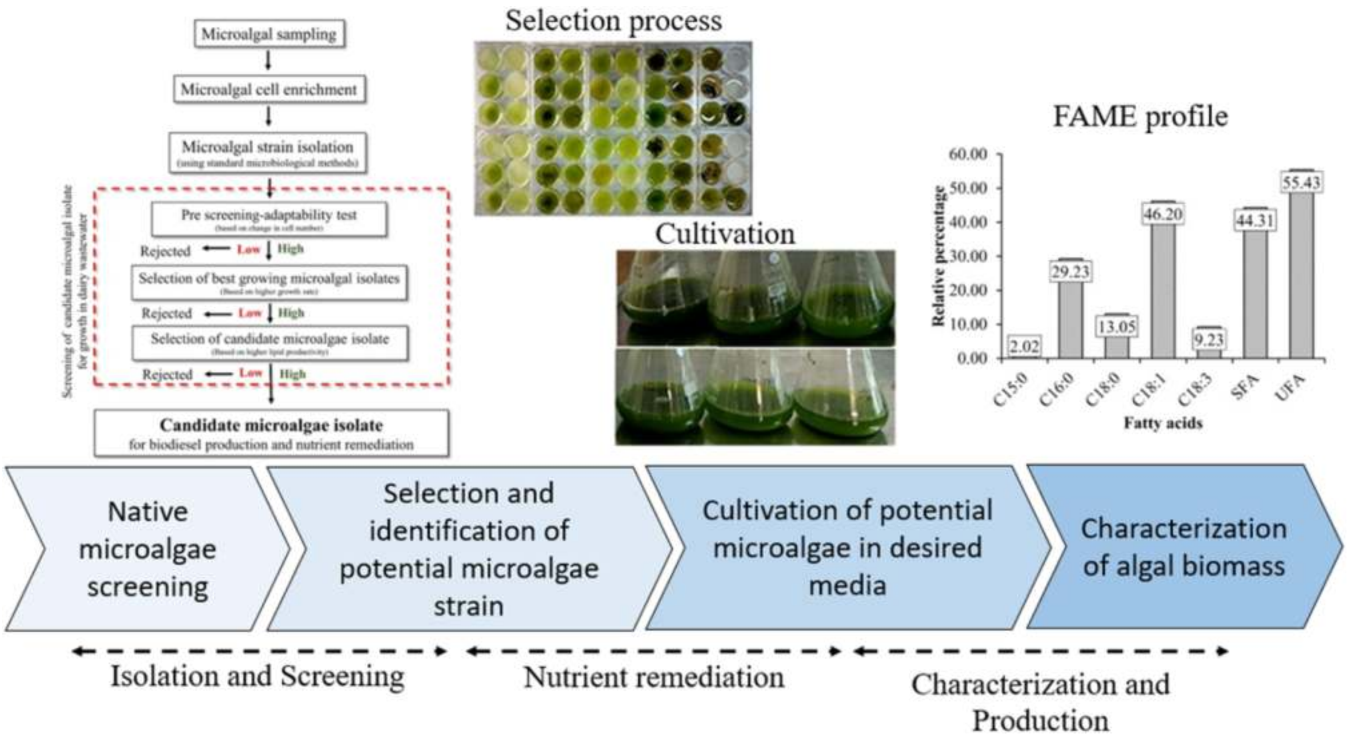


Fig. 13. Selection process of microalgae species for biofuel production from dairy effluent (Pandey et al., 2019).

Table 7
Selection criteria of microalgae species for different applications.

Application	Selection criteria	Ref.
Carbon dioxide sequestration/ fixation	High carbon dioxide tolerance Tolerance on trace elements in flue gas High temperature tolerance Marine microalgae Carbon dioxide assimilation ability Light condition Solid support	(de Morais and Costa, 2007; Ono and Cuello, 2003)
Bicarbonate-based integrated carbon capture	Growth in high bicarbonate condition Tolerance in high pH Salt water species	(Chi et al., 2014)
Wastewater nutrient removal	Chemical Oxygen Demand (COD) removal efficiency Total Nitrogen (TN) removal efficiency Total Phosphorus (TP) removal efficiency Biomass growth	(Álvarez-Díaz, Ruiz, Arbib, Barragán, Garrido-Pérez and Perales, 2017; Wang et al., 2017)
Biodiesel production	Lipid production Fatty Acid Methyl Ester (FAME) composition Fuel properties Biomass productivity Rapid and synchronized lipid production Harvestability of microorganism Oil extractability	(Duong et al., 2012; Islam et al., 2013; Rodolfi et al., 2009; San Pedro et al., 2013; Wilkie et al., 2011)

conditions (Ono and Cuello, 2003). Zhao et al. (2015) examined certain microalgae species for CO_2 fixation based on growth rate and rate of CO_2 in the absence of toxic compounds, and concluded that *Chlorella sp.* was superior in terms of CO_2 fixation compared to *Isochrysis sp.* and *Amphidinium carterae*. Park et al. (2020) investigated microalgae species under different aeration conditions to identify the optimal strain for CO_2 fixation, where *Chlorella sp.* (AG10133) was selected due to best fixation rate of 1.785 g/L at 15 % CO_2 concentration in batch cultivation.

Sodium bicarbonate was proposed as an alternative carbon source for microalgae cultivation in offshore cultivation. Compared to CO_2 aeration, the bicarbonate approach simplifies the structure of PBR by removing the aeration equpments, which avoid issues for scaling-up. Microalgae species selection is also crucial for the bicarbonate approach as the variation of pH due to bicarbonate concentration might have diverse effects on the microalgae species. For instance, the selection of alkalihalophilic *Trebouxiophyte* with high bicarbonate tolerance for the study of carbon utilization efficiency in varying bicarbonate concentrations (Zhu et al., 2021). The strain was selected through a bicarbonate adaptation process. The outdoor cultivation of the species was able to achieve biomass productivity of 0.603 g/L and carbon utilization efficiency of 22.61 % when placed in an optimum bicarbonate concentration of 300 mmol L^{-1}. Similarly, *Leptolyngbya sp.* DUT 001 isolated from contaminated *Spirulina platensis* culture also displayed potential of growing under bicarbonate influence (Zhu et al., 2020a). *Leptolyngbya sp.* DUT 001 was able to have outstanding bicarbonate tolerance of 25.2 g/L compared to screened species of *Leptolyngbya sp.* which only has bicarbonate tolerance of 4.2 g/L.

Another essential note is selecting microalgae species native to the environment as a potential species for the desired application (Mutanda et al., 2020). For instance, de Morais and Costa (2007) isolated species from wastewater ponds nearby a coal-fired thermoelectric generating station, and then investigated their biomass productivity in different CO_2 concentrations to identify the capability of the species for bio-fixation of CO_2 in the power plant. Isolating species in the vicinity of the power plant provides an advantage where the strain is not dependent on the acclimatization of non-indigenous strains to the local cultivation conditions of the power generating station. Wijayasekera et al. (2020) explored the possibilities of CO_2 mitigation for flue gas from a cement factory using *Desmodesmus sp.*, a locally isolated microalga. Although *Chlorella sp.* had a higher gross caloric value, *Desmodesmus sp.* showed higher CO_2 tolerance under diluted flue gas (15.50 % CO_2) condition.

3.3.4. Hydrodynamics loads on floating PBRs

When floating PBRs are immersed in the water, they are subjected to hydrostatic and hydrodynamic forces (Mei et al., 1983). Studies on dynamics of the floating body deals with the interaction between surface water waves and the floating body, affected by factors such as body geometry and wave conditions, as illustrated in Fig. 14(a). This provides an estimation of the behaviour of the floating body in water contributing to the design, construction, installation, and operation of fixed or floating structures (Massie and Journée, 2001). Most floating PBRs proposed by researchers did utilize water surface, but they did not address the motion of the floating PBR in response to the motions on the water surface, showing lack of study on the hydrodynamic motion of the floating structure. As PBRs are partially filled containers, effects of sloshing on the microalgae culture and the PBR structure should also be attended to (Pal and Bhattacharyya, 2010).

Next concern is the unpredictable wave conditions of the ocean surface. Variability of the wave climate frequently interferes with the plan of utilizing renewable wave energy for mixing microalgae culture. Extreme wave conditions, such as rogue waves, storm surges and meteorological tsunamis, as shown in Fig. 14(b) make it difficult to ensure that the mixing rate in the PBR to reach optimum condition for the microalgae species to have high growth rate or able to survive the mixing conditions, as certain microalgae species are fragile to high shear stress conditions (Acién et al., 2017). Mixing and aeration might generate hydrodynamic stress, thereby aeration requires careful consideration, which is essential in large-scale microalgae cultivation, because if in excess, can instead cause decrease in cell growth and biomass productivity, extreme cell damage, or cell lysis (Rodríguez et al., 2009). Shear stress is mainly caused by the formation of eddies during mechanical mixing and bursting of bubbles during aeration. For example, in a bubble column PBR, the biomass production of *C. vulgaris* grown semi-continuously achieved most growth at aeration rate of 0.16vvm, but decreased to cell fatality at 0.19vvm (Khoo et al., 2016). Therefore, it is important to study the range of mixing intensity of shear stress that a specific microalgae species can withstand (Gao et al., 2018).

During calm weather at sea, there are only small or no wave conditions, therefore mixing effect due to external motion is the lowest; consequently, poor mixing accumulates high dissolved oxygen in the microalgae culture, causing low biomass productivity (Costa and de Morais, 2013). Ugwu et al. (2007) observed that *Chlorella sorokiniana* experienced cell lysis and death when dissolved oxygen exceeded 200 % air saturation. Oxygen buildup in enclosed reactors would be a serious problem, especially for small diameters, as the low volume per unit surface area limits the outgassing of oxygen into the atmosphere. For instance, a 1 cm tubular PBR may build up 8–10 mg oxygen per litre per minute (Weissman et al., 1988). According to Zhu et al. (2017), the levels of dissolved oxygen will elevate if there is insufficient mixing. In low wave conditions, increase in harvesting cycles will increase the productivity, as pumping in and out of liquid enhances the mixing of the microalgae culture (Novoveská et al., 2016). Control solutions are needed to improve the mixing rate of the PBR during poor mixing actions, such as by increasing the aeration rate during calm weathers powered by renewable solar energy.

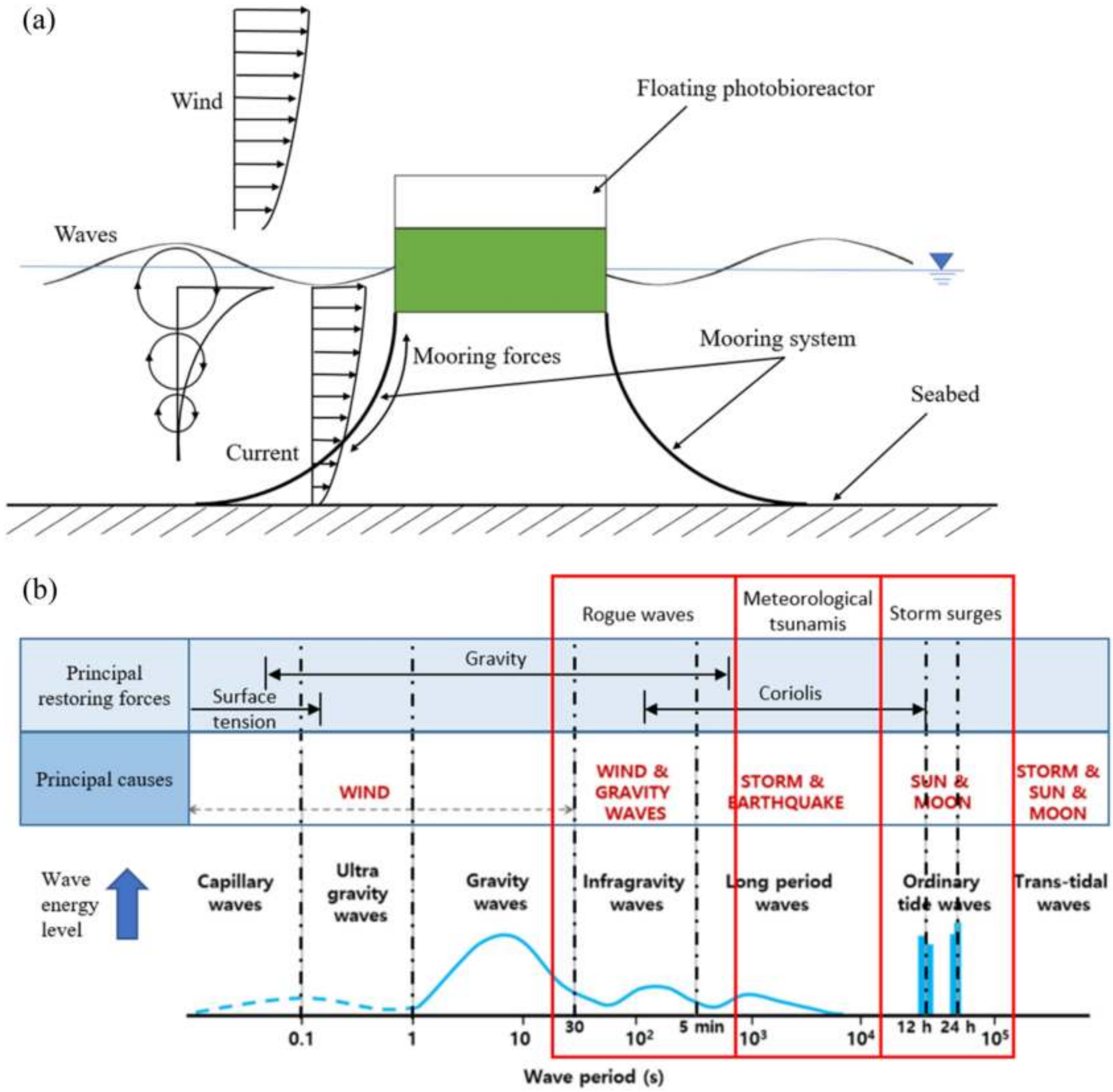


Fig. 14. (a) Environmental loads on floating structures (Ma et al., 2019); (b) Classification of ocean waves (Garrison, 2012; Oh et al., 2020; Rabinovich, 2020).

4. Opportunities of offshore microalgae cultivation with other industries

4.1. Marine aquaculture

Integration of offshore microalgae cultivation with marine aquaculture forms a closed loop system. Wastewater rich with phosphorus and nitrogen is useful as a nutrient for microalgae cultivation, whereby the algae biomass cultivated may be utilized as aquaculture feed, which helps in improving marine aquaculture quality (Knuckey et al., 2006). For example, Shyu (2018) investigated the feasibility of integrating a floating membrane algae PBR system to tilapia aquaculture. It was proposed that the floating membrane algae PBR can be used for removing nutrients from fish waste, with the potential of converting wastewater into value-added algae products. *Chlorella vulgaris* was cultivated in a membrane PBR to remove nutrients from waste produced by fish in the water, yielding approximately 350 mg/L of algae, besides assisting in pH stabilization, ammonia removal, and increasing the dissolved oxygen of the system. The integrated system showed potential as a sustainable option for aquaculture (Wang, 2003) and as a multipurpose tool for aquaculture effluent treatment, as illustrated in Fig. 15.

One of the main applications of microalgae is as feed, where animal feed makes up to 30 % of the algae production (Becker, 2007). For aquaculture, microalgae are mainly used as crustaceans, larval fish and molluscs. Microalgae are a cheaper substitute of protein for aquaculture feeds, besides having additional nutritional values, such as vitamins and polyunsaturated fatty acid (Sirakov et al., 2015). Usage of algae in aquaculture has been claimed to increase body weight, improve protein deposition in muscle, increase in triglyceride, increased immunity, as well as enhance digestibility, physiological activity, starvation tolerances and carcass quality (Richmond and Hu, 2013). For example, *Chlorella sp.* and *Spirulina sp.* can enhance colouration and yield a healthy appearance of fish when added in ornamental fish feed.

Cultivation of *Chlorella vulgaris* and *Isochrysis zhangjiangensis* in floating PBRs also shown potential as feed for aquaculture. A research by Zhu et al. (2019b) studied the cultivation of *Isochrysis zhangjiangensis* in a floating photobioreactor. The floating PBR system was able to achieve biomass productivity of 0.115 g/L day^{-1}, which display promising results for producing fresh aquaculture feed close-by to fish farms. Another study by Zhai et al. (2020) examined the feasibility of cultivation of *Chlorella sp.* in bicarbonate-based seawater on a floating PBR. The bicarbonate-based seawater medium in a floating PBR was able to achieve productivity of 0.190 g/L day^{-1}, which is higher than land-based culture systems. The research shows potential of the utilization of ocean resources for aquaculture feed, such as wave energy for mixing, seawater for medium preparation and temperature control. Both

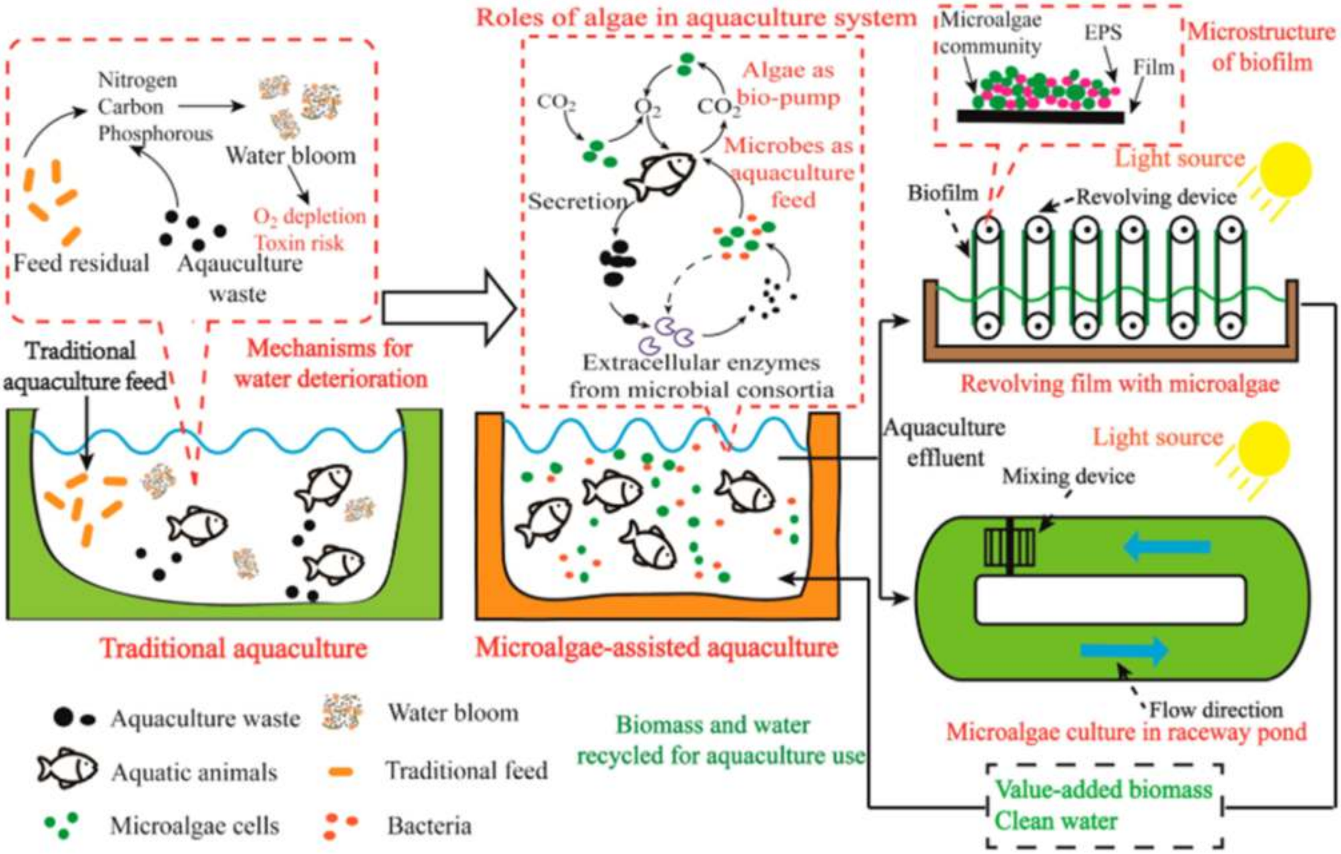


Fig. 15. Integration of microalgae cultivation with aquaculture (Han et al., 2019).

researches are able to provide low-cost floating microalgae cultivation methods that can integrate with marine aquaculture.

As wastewater from intensive fish farms will contain high amount of solid particles and dissolved nutrients, microalgae can be used for wastewater mitigation for removal of inorganic and organic matter (Hawrot-Paw et al., 2020; Tossavainen et al., 2019). Microalgae have been proven as efficient in absorbing phosphorus and nitrogen in wastewater and convert them into useful biomass. This bio-remediation method is efficient, environmentally friendly, relatively low-cost (Colt and Schuur, 2021), and is a simpler sewage treatment method compared to standard wastewater treatment techniques.

4.2. CO_2 capture and utilization from offshore oil rigs

CO_2 is an important source of inorganic carbon for microalgae cultivation. Rather than treating flue gas as a waste product that is associated with significant pollution issues, CO_2 available in flue gas could be utilized for microalgae cultivation. Microalgae can convert inorganic carbons into oxygen and useful products through photosynthesis. The theoretical potential of algae photosynthesis accounts up to 50 % of the world's CO_2 assimilation (Darzins et al., 2010). In accordance with finding by Chisti (2007), microalgae are much more suitable for CO_2 mitigation compared to terrestrial crops, as 1 kg of dry algae biomass can seize about 1.83 kg of CO_2. Normal atmosphere contains about 390 ppm of CO_2, thus it is insufficient to utilize CO_2 straight off the atmosphere for microalgae production (Chisti, 2013). For maximum photosynthetic efficiency of microalgae, about 1–5 % of CO_2 by volume is required.

Algae production plants could provide an alternative carbon capture, storage, and utilization method compared to other CO_2 capture and geo-sequestration methods. Carbon capture and storage have developed into unavoidable requirement in the industrial community, especially to energy providers and industries releasing huge amounts of CO_2. This is similar for oil rigs, where CO_2 production is the second largest source of greenhouse gas, accounting up to 34 % of the global emissions (Klein, 2019). Pipelines of flue gas can also be connected from offshore oil rigs to the offshore algae PBR for CO_2 sequestration. Offshore oil rigs continuously flare unwanted natural gas or sour gas to relieve valve pressures. The CO_2 produced from the combustion of natural gas is either released directly into the atmosphere or temporarily stored in deep sea or depleted oil reservoirs. However, temporary storage of CO_2 in deep sea or depleted oil reservoirs is not a sustainable method, thus more researches need to be done on the long term effects of the underground storage of CO_2 (Raza et al., 2018; van der Meer, 2005). Eventually, the CO_2 will affect the acidity of sea water and be released back into the atmosphere. According to Darzins et al. (2010), even though the southwest of the United States has 2500 kilometres of pipelines to convey beyond 40 Mt/year of CO_2 from oil production wells to be injected underground elsewhere, the transport of CO_2 over long distances overseas causes extra charges for liquefaction and shipping, which have immense consequences on algae production. Thereby, offshore PBRs are potentially cheaper alternative to process CO_2 from production wells instead of paying for transporting it.

Another example is a study on *chlorella vulgaris* with regard to its capability on CO_2 fixation rate through bubbling of different CO_2 concentrations in a bubble column PBR. Through optimization, the maximum CO_2 fixation rate of 2.22 g per litre was obtained daily under 6.5 % CO_2 and 0.5vvm after a week (Anjos et al., 2013). Microalgae obtained in vicinity of power plants or industrial plants can also be analysed for CO_2 sequestration potential. Wijayasekera et al. (2020) conducted research on *Desmodesmus sp.* obtained nearby flue gas source, which yielded CO_2 fixation rate of 0.26 $gL^{-1}day^{-1}$ and biomass productivity of 1.17 gL^{-1} under undiluted flue gas with 15.50 % CO_2, which had higher CO_2 fixation rate compared to *Chlorella sp.* in their study.

Additionally, another carbon capture method suitable for integration with floating structures is by direct air capture (DAC) of CO_2 from ambient air. The concept is to take advantage of the high absorption rates of CO_2 into the carbon pool with the increase of pH and high concentration of bicarbonate (Piiparinen et al., 2018; Vadlamani et al., 2019), mimicking soda lakes. In dark, the carbon pool efficiently captures and stores CO_2, whereas when light is available, fast growing alkalihalophilic microalgae species utilize the bicarbonate for photosynthesis and release oxygen into the atmosphere. Zhu et al. (2020b) demonstrated the concept of direct air capture using *Spirulina sp.* DUT001 and achieved biomass productivity of 1.00 g/L d^{-1} and carbon capture rate of 0.81 g/L d^{-1} in a bicarbonate pool of 100–500 mmol L^{-1} bicarbonate and pH of 10.0–12.5. It is also suggested that the carbon pool concept can be incorporated with an air-compressing device driven by wave energy to reduce energy cost.

4.3. Source of hydrogen

Photobiological hydrogen produced from cyanobacteria and microalgae also draws interest as a potential, reliable and renewable energy source alternative. Hydrogen gas has high energy yield, besides being highly efficient, versatile, and renewable clean energy that could substitute fossil fuels. Hydrogen is the most advanced CO_2 free fuel that can provide energy while only emitting ware and no other pollutant emissions. Several microalgae species such as *Chlamydomonas reinhardtii*, *Chlorella vulgaris*, *Scenedesmus obliguus*, and *Tetraspora sp*. had been investigated for their significance in hydrogen production (Khetkorn et al., 2017). Hydrogen production by green microalgae is related to direct bio-photolysis process, particularly when algae cultures are placed under light after an interval of dark anaerobic adaptation, as presented in Fig. 16(a). Through comparative analysis, flat panel PBRs are preferable for hydrogen production to avoid backpressure due to collective hydrogen (Nyberg et al., 2015).

For hydrogen production, agitation methods are also crucial, where agitation by sparging will lead to elevated changes of leaks, whereas mixing by mechanical stirring requires high energy input (Skjånes et al., 2016). Thus, agitation by rocking motion which utilizes the wave motion on the sea surface may have practical uses. Otsuki et al. (1997) utilized wave motion to mix liquid in the floating PBR, achieving hydrogen production of 597.7 litre hydrogen per irradiation area within duration of 66 days.

According to a technoeconomic analysis conducted by Gholkar et al. (2021), hydrogen production of microalgae using reactive flash volatilisation (RFV) produced 36 % less greenhouse emissions compared to the current hydrogen production based on steam reforming of methane gas. Replacement of electricity with renewable energy processes was found able to further reduce carbon emissions by 87 %, at 1.72 kg CO_2-eq/ kg H_2. However, hydrogen production from wind energy driven

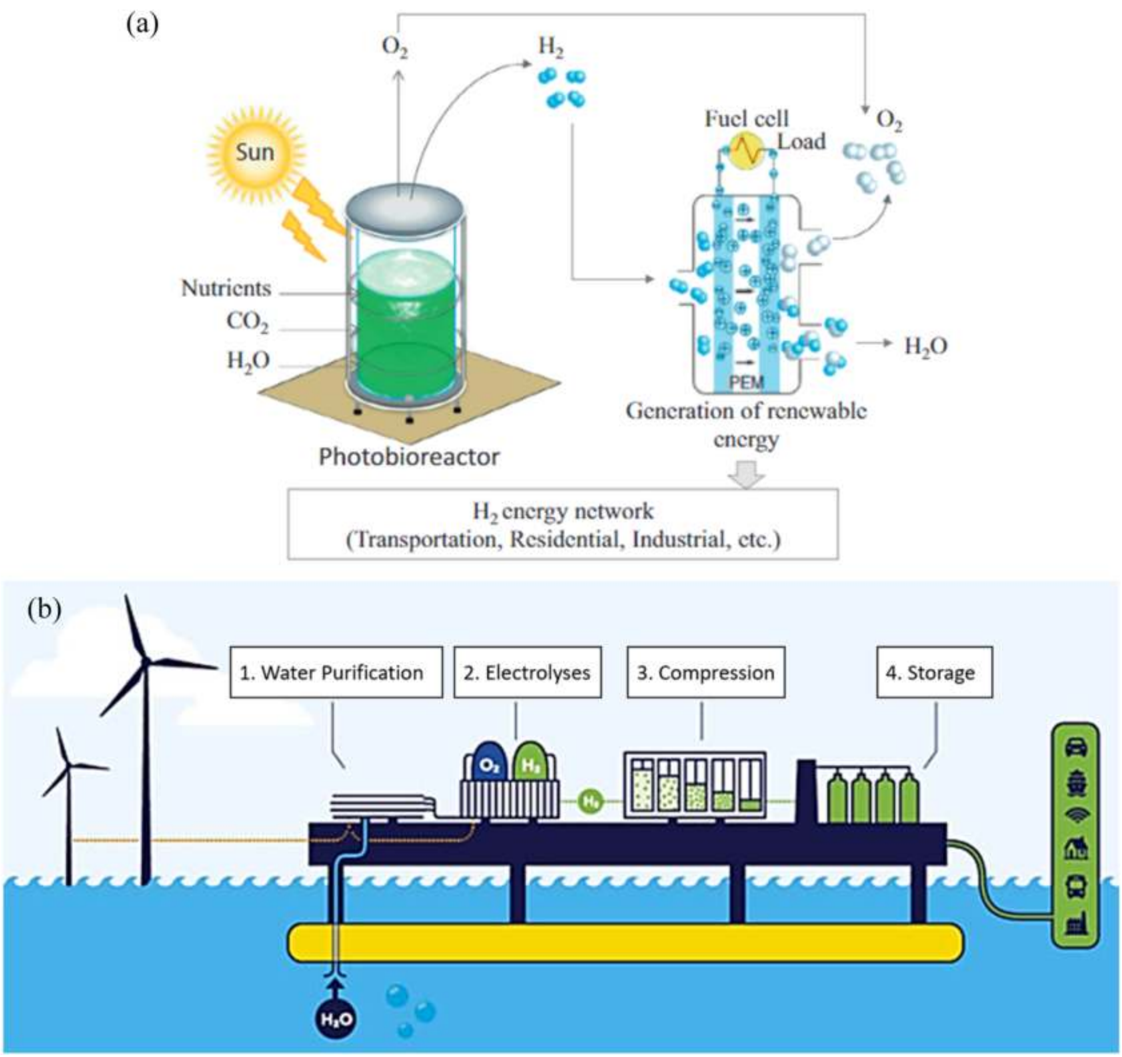


Fig. 16. (a) Hydrogen generation from microalgae (Khetkorn et al., 2017); (b) Four-step process of offshore floating hydrogen production facility. (Retrieved from DNV GL on 6th October 2021).

water electrolysis provides an even lower impact of 0.97 kg CO_2/ kg H_2. Integration of hydrogen production with offshore decommissioned platforms could provide a solution for the production, storage and transportation of hydrogen, as illustrated in Fig. 16(b). The offshore floating hydrogen facility could provide greener hydrogen, without being limited in term of land-space. Despite the fact of lower environmental impact of wind-energy driven water electrolysis, hydrogen production from microalgae still provides additional benefits of wastewater treatment and absorption of CO_2.

4.4. Ocean thermal energy conversion

Ocean thermal energy conversion (OTEC) utilizes temperature fluctuations between the warm tropical oceans (22–24 °C) and the colder deep waters (4–8 °C), which has a temperature difference of about 20 °C to produce electricity (Wang et al., 2011), as shown in Fig. 17(a). However, compared to other energy productions, OTEC has only about 10 % thermal energy conversion efficiency; up to 90 % extracted energy are wasted. This leads to the need of integration of OTEC with other environmental benefits and integration of marketable by-products, such as desalination of water, reduction of CO_2 emissions, and deep sea mariculture and agriculture, benefiting from stable ocean surface temperature and nutrient-rich deep sea water (Masutani and Takahashi, 2001).

Deep ocean waters are rich in nutrients, cold, and pure, as there is little life at depths (Thomas H. Daniel, 1994). The cold deep ocean waters can serve as a suitable habitat for growing marine organisms, for example, oysters, lobsters, macroalgae, and microalgae, which offers profitable high-value products, as demonstrated in schematic diagram of OTEC in Fig. 17(b). The cold sea water can also reduce surface temperature to stimulate low temperature conditions for equatorial weather. Ocean thermal energy can also be used to manipulate microalgae culture. Variations of temperature have different effects on the growth, biochemical and fatty acid composition of the microalgae (Anuwar, Teoh, Yap, Ng and Phang, 2020; Teoh et al., 2013).

4.5. Desalination

Desalination of seawater is one of the most feasible approaches to convert seawater or brackish water into safe drinkable water by removing excess salts. The energy-intensive process generates freshwater from seawater and the wastewater is commonly discharged back into the sea. Although the seawater desalination process is able to offer benefits of high-quality drinking water and preserving existing natural water, the enormous amount of desalination concentrate wastewater or brine may have adverse effects on the environment (Ihsanullah et al., 2021). The waste stream is high in salinity, with total dissolved solids up to 80,000 mg/L (Miller et al., 2015) besides being high in temperature and contains various heavy metals, by-products, and residues of chemicals used in the desalination process. The discharges may alter the temperature, salinity, turbidity, and dissolved oxygen level of the marine habitat (Alharbi, Phillips, Williams, Gheith, Bantan and Rasul, 2012; Cambridge, Zavala-Perez, Cawthray, Statton, Mondon and Kendrick, 2019; Sharifinia et al., 2019).

Saline effluent treatment technologies are mainly based on physical and chemical technologies, such as evaporation, membrane techniques, electrochemical techniques and advanced oxidation processes (Sahu, 2021; Zhao et al., 2020). Although physicochemical processes are more common applications, bioremediation using microalgae for the removal of mild saline effluent with the salinity range of 5–10 % is also plausible for treatment of pollutants suitable as nutrients for microalgae (Vo et al., 2020). For example, the cultivation of *Dunaliella salina* using seawater desalination concentrate as a culture medium to produce β-carotene. The saline effluent pre-treated to remove calcium and magnesium was able to yield 300 g biomass containing 14.3 g β-carotene from 1000 litre of saline effluent (Zhu et al., 2018a). The integration of a microalgae culture system close by to the seawater desalination plant could assist in reducing saline effluent and produce valuable by-products to improve the profitability of the desalination plant.

5. Challenges in using floating PBRs

From the various types of floating PBRs in Table 3, researches on these devices are still mainly in the infancy stage, and it is expected to take more efforts to be materialized. Feasibility of deploying floating PBRs for offshore microalgae installation requires consideration of various fields. Installation of floating PBRs in marine environment exposes the floating structures to similar challenges of sea as faced by ships and offshore structures (Tiron et al., 2015), while retaining similar challenges to onshore PBRs in terms of nutrient availability and

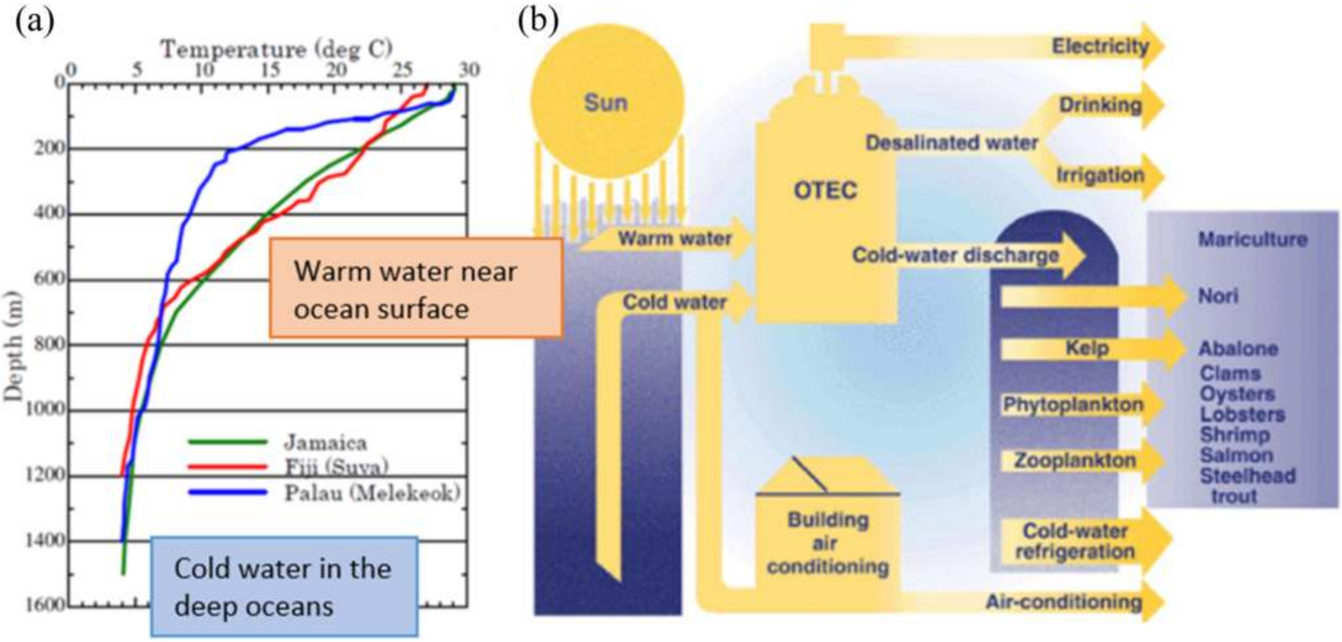


Fig. 17. (a) Ocean water temperature; (b) Schematic diagram of OTEC (Salameh, 2014).

commercializing issues. Ocean waves are random and unpredictable, which may be useful or destructive, and the marine habitat that holds home to millions of species has undesirable effects on semi- and fully submerged structures. Challenges faced by floating PBRs involve selection of offshore locations, microalgae species selection, as well as hydrodynamic, biological, economic, environmental, installation, and maintenance issues.

5.1. *Biofouling on floating PBRs*

Biofouling has always been a threat to structures immersed or nearby marine environment. The build-up of microorganisms on the surface can lead to increase in roughness of the ship hull, in addition to structural and functional deficiencies of floating structures. Build-up of microorganisms on the semi-permeable membrane PBR reduces diffusivity of the membrane, thus limiting the nutrient intake of the floating PBR (Harris et al., 2013). Biofouling also causes decrease in light transmission through the transparent structure, leading to decrease in microalgae biomass. Commonly used antifouling treatment for ship and offshore structures is copper antifouling paint, which has a lifespan of 3–5 years, with the toxic content of the paint continuously sipping into the marine environment.

For PBRs, transparent antifouling coatings are required to retain light penetration properties. For instance, clear silicone antifouling coatings can retain light penetration properties with antifouling effects (Hu et al., 2020). The silicone antifouling surface cannot inhibit attachment of the biofouling organisms, but the weak bonding between the organisms and coating surface due to low surface free energy will eventually cause the attached organisms to be removed by water shear force. Another possible method, suggested by Kim et al. (2019), is grafting a semi-permeable membrane using hydrophobic 4-*hydroxyphenethyl bromide* to reduce biofouling. The 4-*hydroxyphenethyl bromide* is used to increase water contact angles and reduce the hydrophobicity of semi-permeable membrane, which can achieve biofouling reduction of up to 40 %.

Besides effects on the growth of marine organisms on floating PBR, the effects of biofouling on the performance of device should also be evaluated. Although the growth of fouling organisms might be insignificant at start, the accumulation of marine population on the floating PBR will increase the weight of the structure. For example, Tiron et al. (2015) observed that the growth and accumulation of mussels on a concrete panel submerged in sea had increased the weight by 250 kgm^{-2} in duration of 216 days. Fouling on the floating structure will also increase the drag of the floating structure, which might have negative effects on wave energy harvesting structures.

5.2. *Techno-economic challenges*

Techno-economic analysis for microalgae production is essential to assess the total production cost, which is dependent on the product obtained, production process, and production capacity. Major inputs to the production expenditure include raw materials, labour, utilities, depreciation, and supervision. Trent (2012) conducted techno-economic analysis for the OMEGA prototype for extensive algae cultivation and sewage treatment, covering the estimation of revenue required (RR), energy return on investment (EROI), and greenhouse gas (GHG) emissions. The EROI for wastewater treatment OMEGA prototype was 1.02, with RR of $16 M/y and GHG of − 19.14 kg of CO_2 per litre of wastewater. High economics is also dependent on geographical area, cultivation variation due to different seasons, labour costs, solvents used, and other factors (Dutta et al., 2016). Production costs need to be reduced by development of economical technologies and incorporation of valuable co-products to improve economic feasibility of microalgae cultivation (Kang et al., 2020).

Techno-economic assessments are tedious to be conducted at the initial phases of PBR design, especially for small prototypes. Even for well-established large-scale prototypes, techno-economic assessments are firstly conducted based on various assumptions, such as a hypothetical engineering process model, assumed energy consumption, and estimated productivity of the PBR prototype. Detailed flowchart of the production capacity and kinetic parameters are required, as well as the type and size of equipment, along with mass and energy balances on the entire process, from upstream to downstream processes (Acién et al., 2013).

As floating technologies are still in the infancy stage, upsizing the scale of floating PBRs and progressive design improvements are necessary to advance with a comprehensive techno-economic analysis (Dogaris et al., 2015). Major challenges of techno-economic analysis come into view especially when the process or technology is in the process of scaling up to commercial levels. It is essential to consider economics cost and appoint optimized parameters into the calculation, for instance, market power issues, transportation and storage, and environmental impacts. Martins (2019) evaluated whether a floating photovoltaic project is more cost-effective compared to ground located photovoltaic technology. The concerns mentioned included the effects of moisture atmosphere on the lifetime of the technology, effects of water environment on the efficiency levels, selection of mooring and anchoring systems, and competency of data tracking device, besides the consequences of installation on the environment, particularly on influence of construction, operation, and decommissioning phase of the floating technology.

5.3. *Leakage of algae from floating PBRs*

Algae blooms will occur in waters with excess of nutrients (particularly phosphorus and nitrogen land run-off), notably by rapid growth of algae and green plants (Kraan, 2013). Algae are beneficial to natural freshwater and marine habitats in small amounts. However, once above a threshold level, the algae block off the penetration of light, besides contributing to significant amount of dead organic matter, which then increases the number of bacteria. Bacteria use up the dissolved oxygen in the water to decompose dead organic matter, resulting in the death of fish and aquatic insects. Uncontrollable microalgae bloom will disturb the entire ecosystem, from blockage of sunlight, dissolved oxygen depletion, and possible discharge of toxins into the habitat (Usher et al., 2014). Direct contact of PBRs with the marine habitat, might also pose a threat to the ecosystem if leakages occur. PBRs filled with nutrients and microalgae species, may also cause algae blooms if not treated attentively. Algae blooms may also produce neurotoxins that have severe biological impacts on wildlife. Although microalgae are beneficial to remove nutrient from wastewater, the leakage of microalgae which are highly adaptive to the environment into natural freshwater and marine habitats that contain excess nutrients, might be deadly to the habitat.

Spills of cultured microalgae into the environment may also cause unpredictable and fluctuating species balance to the natural ecosystem, such as mutated or transgenic strains of identical species, which will have varying behaviour compared to native species, depending on the size of the spill (Gressel et al., 2013). For minor spills, if the algae do not have fitness advantage or are a non-native species, the spill might be quickly diluted. However, for a major spill, the species composition might be affected as they remain alive. Assuming that the cultivated species are robust and equally competitive to native species, an irreversible effect might occur on the microorganisms, causing transgene(s) in the algae. Thus, adequate biosafety measures are needed to dilute the effect of major microalgae spills.

5.4. *Installation and maintenance of floating PBRs*

Installation and maintenance of offshore structures are extremely complex as they involve demanding logistical challenges influenced by remote locations, stormy weathers, such as wind, wave, and current, besides the naturally permanent corrosive environment. Challenges include demanding requirements for safety and reliability of the structure, besides the aim to deliver a cost-effective offshore facility. Considering the life cycle of offshore facility, decommissioning planning should also be assessed (Moan, 2018). Throughout the life cycle of offshore structures, from design, fabrication, installation, operation, and decommissioning, all these processes require detailed planning to ensure structural reliability, besides being cost and time efficient. Similar for the installation and maintenance of offshore microalgae cultivation systems, either a sole structure or combination with other offshore industries, there is a need to consider the risk and reliability methodologies to ensure the safety of the structures.

5.5. Destructive hydrodynamic loads

In extreme wave conditions, the floating structure will be subjected to the threat of destructive energy (Zhang et al., 2021), such as slamming effects. Wave slam impacts can occur due to the external waves or the contained liquid due to sloshing. Support structures suffer impact forces when engaged with incident waves, while the wave impacts due to external waves forces are concentrated on the splash zone. For example, slam forces are estimated equal to 2150 tonnes of weight for a scaled vessel having weight of 2500 tonnes (Lavroff et al., 2017), to cause strain energy up to 3.5 MJ on the structure, and impulses on the bow up to 938 tonnes weight-seconds. The impact energy is often transferred along the structure in longitudinal whipping mode, which may lead to undesirable damages and vibrations on the structure. It is necessary to identify impact pressure using load reduction techniques to reduce the impact of slamming events.

6. Conclusion and recommendations

This paper has outlined the development of floating PBRs and highlighted a number of mixing parameters. PBRs designed for microalgae cultivation on open waters have been thoroughly described. Floating PBRs are designed mainly to overcome land competition, besides other advantages such as temperature regulation and renewable external mixing energy. However, challenges remain for the industrialization of floating PBRs, such as location selection, algae selection, hydrodynamic issues, biological issues, economic challenges, and environmental challenges. The importance of these challenges has been described in detail, since their importance has been understated in literature. Besides these challenges, integration of floating microalgae cultivation with other offshore industries has also been discussed to strengthen the economic practicability of floating PBRs.

Further studies on floating PBRs should include hydrodynamic performance and sloshing of internal liquid when subjected to the wave conditions, besides emergence of innovative materials suitable for deployment in marine environment, and potential impacts of the positioning of PBR in marine environment for the development of floating PBRs at commercial scale. There is also a need for further studies on wave energy harvesting methods for direct use of mixing and mass transfer for microalgae cultivation, besides designing control methods to control the mixing and mass transfer in the floating PBR during intermittent wave conditions. There is potential for integration of floating PBRs for microalgae cultivation in offshore areas. However, studies are still at infancy stage compared to land-based PBRs. In summary, specific challenges related to floating PBRs have been addressed, and future possibilities of microalgae cultivation in the offshore areas have been outlined.

CRediT authorship contribution statement

Wei Han Khor: Conceptualization, Writing – original draft, Writing – review & editing, **Hooi Siang Kang:** Conceptualization, Supervision, Writing – review & editing, **Jun-Wei Lim:** Resources, Writing – review & editing, **Koji Iwamoto:** Supervision, Resources, **Collin Howe-Hing Tang:** Supervision, Methodology, **Pei Sean Goh:** Resources, Writing – review & editing, **Lee Kee Quen:** Resources, Methodology, **Nik Mohd Ridzuan Bin Shahruddin:** Writing – review & editing, **Nai Yeen Gavin Lai:** Writing – review & editing.

Declaration of Competing Interest

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

Acknowledgements

The authors would like to appreciate the Ministry of Higher Education (Malaysia) under Fundamental Research Grant Scheme (FRGS/1/2020/TK0/UTM/02/49) for the supports in preparing this paper.

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