

Potential of household photobioreactor for algae cultivation

Ashrakat Osama, Hadeel Hosney and M. S. Moussa

ABSTRACT

Biotechnology harbors stunning potential to provide cutting-edge solutions that can mitigate arising environmental issues which impact developing countries more severely. Although considerable projects have been implemented in these developing nations to reduce the consequences of climate change, global warming, and food insecurity, most of the initiatives are deemed unsustainable or unfulfilling. Consequently, millions of individuals are still suffering from unhealthy environments and others have limited access to clean technologies. Accordingly, this manuscript is developed to act as a one-stop source for technical perspectives of microalgae cultivation and proposes the potential of scaling down of a photobioreactor (PBR) from industrial to household level to alleviate adverse environmental implications. The household PBR proposal is concerned with microalgae cultivation that contributes to mitigating CO₂ from the surrounding environment and synthesizing a product that could be of high nutritional value. Additionally, the business model of household PBR is developed in accordance to low and middle-income countries' demands to facilitate future projects in this scope. The value proposition of this model relies on decreasing climate change impacts, enhancing wellbeing, and providing natural supplements. Scale of economy, appropriate technology, and socio-economic challenges for household PBR are highlighted.

Key words | algae cultivation, climate change, household scale, microalgae, photobioreactor

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HIGHLIGHTS

- Technical perspectives of microalgae cultivation (species selection, design parameters, types of photobioreactor, downstream processing technologies).
- Resources recovery that exists in wastewater through algae cultivation.
- Potential of scaling down the industrial PBR to household level.
- Challenges and opportunities for algae cultivation industry on a small scale including technical and socio-economic aspects.

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GRAPHICAL ABSTRACT



INTRODUCTION

Climate change is a global threat that needs innovative ideas to cope with such a challenge. Agricultural practice is severely jeopardized by climate change. Indeed, extreme weather, projected increases in daily temperatures (which also increases vermin and pests), unpredictable precipitation patterns, and overall further water supply shortage will reduce agricultural productivity. The major portion of water consumption goes to agriculture and the total evapotranspiration from global agricultural land could double in the next 50 years if trends of food consumption and climate change continue. However, raising the water productivity rates is not the only solution to cover the agricultural needs. During the last 50 years, a ‘water use efficiency’ concept was applied to cover this gap and fulfill the needs but currently the concept has been enhanced to ‘maximum crop per drop’. This new concept is linked with socio-economic and environmental perspectives (UNESCO WWAP 2017). There is a need to incorporate this concept with all stakeholders’ plans and strategies to find alternate nutritious supplies that are also affordable, durable, and sustainable to avoid reaching food insecurity boundaries.

Algae are highly diverse species that are related to photosynthetic protists with relatively simple morphologies (Anderson & Lewin 2015). They are usually seen in shallow water that is rich in nutrients on which they thrive, causing eutrophication. Algae species that thrive in this uncontrolled manner in unclean water bodies are harmful for human consumption. This fact has overseen its potential as a natural treatment process for nutrient recovery. The gross chemical compositions of algae are protein, carbohydrates, and lipid. The chemical composition of microalgae varies from one species to another (Chang *et al.* 2017; Velazquez-Lucio *et al.* 2018). Microalgae are more efficient at photosynthesizing

and thus they capture more CO₂ efficiently than regular land-based plants (Packer 2009; Sayre 2010). They thrive on nitrogen, phosphorus, and potassium in water, which are major run-off pollutants from farmlands.

Algae are so diverse and so complex that it is difficult to classify them all under one name. There are several algal lineages. The most common ones are cyanobacteria, green algae, red algae, diatoms and brown algae (kelps) (Anderson & Lewin 2015). Cyanobacteria are known to be able to fix nitrogen, they can be used as food (Spirulina) and soil conditioners (Stal 2015). Green algae are the most harvested microalgae as they can grow quickly, common species include *Chlorella* (Silva *et al.* 2019). Red algae dominate the seaweed species. They have been used as a source of food for thousands of years as they are rich in antioxidants, vitamins, and minerals (Gomez-Zavaglia *et al.* 2019). Diatoms are known to be rich in oil contents, so they are important in biofuel research (Graham *et al.* 2011). Finally, kelps are large brown algae seaweed found in marine water bodies and they are used in many products such as toothpaste, shampoos, salad dressings, cakes and much more (Shelar *et al.* 2012).

Algae have been traced back as a food source as early as 300 A.D., where written records claim that the Chinese Emperor consumed it (Wells *et al.* 2016). Fast forward to the current century, in 2013, the total harvest of seaweed (macroalgae) was estimated to be worth US\$6.7 billion (FAO 2015). Microalgae are integrated into food additives, skincare products, and nutritional supplements. Overall, there is a growing trend towards the nutritional demand for algal products globally due to their vast health benefits. There are also numerous industries practicing commercial-scale cultivation but there are no records concerning cultivation on a household scale.

Several studies have addressed all the above-mentioned issues without integrating the concepts in a decentralized system at household level. Moreover, there is a serious challenge to bridge the gap between research efforts and a community's needs. Accordingly, finding alternate nutritious supplies through decentralized technology that are tuned towards addressing core life problems and meeting population demands becomes a must.

In this respect, this manuscript is introduced to propose microalgae cultivation at the household level for the first time in developing countries in order to cope with the environmental challenges and needs of poor communities. The first part of the article provides a wide literature review for microalgae cultivation including species, cultivation parameters, photobioreactor design, downstream processing, and economics of cultivating microalgae on household levels, while the second part proposes a business model for cultivating microalgae via a decentralized PBR and the expected challenges that will be encountered with this approach will be discussed. Last but not least, the way forward is proposed to capitalize on these outcomes.

ALGAE CULTIVATION

Photosynthetic organisms such as plants, algae, cyanobacteria, and euglena are all high-potential bioresources that can be used in manufacturing food supplements, animal feed, pharmaceuticals, cosmetics, biofuels, and even wastewater treatments (Priyadarshani & Rath 2012; Huang *et al.* 2017). Algae, however, are a highly diverse group of organisms that include photosynthetic protists and cyanobacteria. There are over 40,000 algae species that have been identified (Suganya *et al.* 2016). They may be unicellular (microalgae) or multicellular (macroalgae). Macroalgae

are mostly seaweed that are found near the seabed while microalgae are microscopic algae found in freshwaters and saline water (Scott *et al.* 2010). Macroalgae require a large area for cultivation while microalgae in photobioreactors (PBRs) take up much less space and require less labor. Both have nearly equivalent potential in food production and therapeutics. However, microalgae have several untapped applications that are still under investigation. Moreover, the cultivation of microalgae can be used to combat global warming. Microalgae can be cultivated in wastewaters and high saline water (certain species) which help tackle environmental problems. All in all, microalgae cultivation could be a doorway to added-value products and applications while tackling global warming and waste problems. Figure 1 depicts an overview of the several processes involved for algae cultivation. First, the selection between microalgae and macroalgae, followed by species selection, and the cultivation conditions that should be followed. In all cases the cultivation would take place in a photobioreactor which is either closed or open. Finally, in the downstream stage, there are several harvesting and dewatering methods which are selected based on the primary wanted bioproduct.

Potential of microalgae

Microalgae are genetically a very diverse group of organisms with a wide range of physiological and biochemical characteristics; thus, they naturally produce high-value chemical compounds, such as pigments, enzymes, and minerals which serve as renewable sources for many commercial applications (Suganya *et al.* 2016; Gujar *et al.* 2019). Their production costs depend on how they are cultivated (open or closed reactors) and for what purpose (nutritional, pharmaceuticals, etc.). Their production cost ranges from a minimum of 5 €/kg for

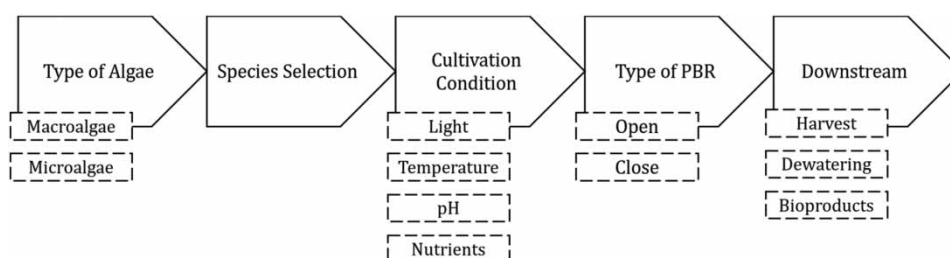


Figure 1 | Algae cultivation processes overview.

raceway reactors to 50 €/kg for tubular photobioreactors (Acién Fernández *et al.* 2013). Figure 2 illustrates the potential benefits from cultivating microalgae for humans, animals, aquatic life, agriculture and climate change.

Food supplement

Microalgae are rich in protein, greater than other vegetable sources carbohydrates, and fats (Mata *et al.* 2010). Some species contain similar amounts of protein found in sources such as milk, soybean, egg and meat (Becker 2007; Bleakley & Hayes 2017; Koyande *et al.* 2019; Amorim *et al.* 2020). They are sold as tablets and capsules and are also incorporated into pastas, snack foods, candy bars and beverages (Suganya *et al.* 2016). They are rich sources of vitamins and minerals such as potassium, iron, magnesium, calcium and iodine (Becker 2003). Additionally, WHO recommended *Spirulina* spp. to be included in NASA's diet as it is an ideal, compact food for space travel and is nutritious even when consumed in small amounts (Khan *et al.* 2005).

Animal and aquatic feed culture

Algae can be a source of improved immune response and fertility, and better weight control for several animals by providing a large profile of natural vitamins, minerals and essential fatty acids (Suganya *et al.* 2016). Indeed, 30% of the microalgae production is sold as animal feed (Richmond 2007). Meanwhile, in the aquaculture field, microalgae are added as fish feed to stabilize and improve the culture medium (Muller-Feuga 2000) and they also act as coloring for farmed salmonids (Chuntapa *et al.* 2003). It also enhances the immune systems of fish while inducing essential biological activities (Pulz & Gross 2004).

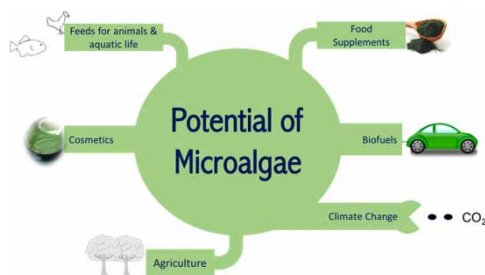


Figure 2 | Potential of microalgae.

Bioactive compounds

Microalgae are rich sources of oils and fats containing omega-3 which is part of a healthy diet that helps lower the risk of cardiovascular diseases (Suganya *et al.* 2016). They are also an excellent producer of carotenoids such as β -carotene and astaxanthin (most commercially produced carotenoids) (Suganya *et al.* 2016). Carotenoids are pigments which can be used as food coloring, supplements, therapeutics, human and animal nutrition, and cosmetics due to their ability to act as provitamin.

Biofuel

Most industries are attracted to the cultivation of microalgae to produce biofuels (Khan *et al.* 2018). Microalgae can in fact make it possible to produce several types of biofuels: biodiesel, biomethane (or biogas), hydrogen, and bioethanol (Giordano & Wang 2017). The usage of biofuels is renewable, sustainable, biodegradable, carbon neutral for the whole life cycle and environmentally friendly (Suganya *et al.* 2016). However, the commercial production of microalgae for biofuel is limited as large volumes of cultures are required to produce significant amounts of biofuels at low prices compared to fossil fuels (Giordano & Wang 2017). However, biofuel is an emitter of greenhouse gases, although it is claimed to be carbon neutral as released CO_2 would be absorbed by the microalgae. The process of biofuel production (extraction, transportation to fuel production plants, then to consumers) makes it release more GHG gases overall and thus it is not recommended to be produced as a potential product of algae cultivation (Hanaki & Portugal-Pereira 2018).

Soil conditioner

Microalgae can be used as soil conditioners as the majority of the cyanobacteria are capable of nitrogen fixation (Priyadarshani & Rath 2012). They can also produce growth promoting substances which can increase maintenance and soil fertility (Song *et al.* 2005). Microalgae can be converted by pyrolysis to 'biochar' that has potential agricultural applications as it can be used as soil with some additives, and for carbon sequestration (Marris 2006).

SELECTION OF MICROALGAE SPECIES

With more than 40,000 species of microalgae, selection of the appropriate microalgae strain requires certain main features that should be taken into account during the microalgae selection process. Table 1 summarizes the main features for selection of microalgae species. Not all microalgae species can be mass cultivated; some are still cultivated on lab-scale. *Chlorella*, *Dunaliella*, and *Spirulina* species have dominated commercial opportunities (Suganya et al. 2016). Table A1 in Supplementary Materials provides a summary of the growth conditions, applications and market value of *Chlorella*, *Dunaliella*, and *Spirulina*.

Cultivation of microalgae

Microalgae are found in lakes, lagoons or ponds and are usually associated with the negative environmental impact phenomenon – eutrophication. They are not present in all ponds naturally, but they thrive upon the existence of high

Table 1 | Main features for selection of microalgae species (Geada et al. 2017)

Features	Description
Growth physiology	This focuses on the specific growth rate of the strain and its growth conditions such as temperature, pH, salinity, O ₂ , and CO ₂ level. The nutrition mode of the microalgae is also focused on whether it is heterotrophic, photoautotrophic etc.
Metabolite production	Microalgae secrete a wide range of secondary metabolites such as sterols, waxes, ketones, hydrocarbons, vitamins, pigments, carotenoids (Vuppaladadiyam et al. 2018), etc. These are all necessary for the implementation of the biorefinery process
Robustness	Susceptibility to external predators, contaminants, reasonable resilience and ability to withstand extreme abiotic conditions are all important characteristics that need to be considered
Amenability to genetic manipulation	The susceptibility of optimizing the performance through genetic manipulation allows the strain to be more flexible with high potential

levels of nutrients, specifically, nitrogen and phosphorus. Their optimum pH to grow at is 8.2–8.7 but they can tolerate pH ranges between 7 and 9 (Bitog et al. 2011). They grow at temperature ranges between 16 and 35 °C (Bitog et al. 2011).

Microalgae are cultivated in open ponds or closed systems called photobioreactors (PBRs). Around 90% of microalgae production industries continue to harvest algae in natural or artificial ponds, i.e. open PBRs (Placzek et al. 2017). However, closed types of PBRs have been proposed in the last decade. Open PBRs are easy to construct and are relatively cheaper than closed PBRs (Moejes & Moejes 2017). There are three types of artificial open ponds: (1) unstirred open ponds; (2) circular controlled ponds; and (3) controlled raceway ponds. Controlled ponds were introduced to accelerate the microalgae growth, but the basic ones were the simple open ponds. The maintenance cost for the artificial open ponds is only limited to the paddlewheel (for raceway ponds) and adequate CO₂ concentrations and they require simple cleaning up procedures. However, the downsides of this type of cultivation are grave. First, they require a large area (Placzek et al. 2017), depending on the production rate, with high solar incidence, so they are typically set up in deserts. Therefore, they are susceptible to contamination brought around by sandstorms or even parasites. This problem usually exists in regions such as the Middle East or Africa. The idea of controlled cultivation has allowed this problem to be overcome worldwide. Second, they are susceptible to thermal shock or photoinhibition due to the extremely high light incidence. It is also difficult to control the temperature of the pond and water loss by evaporation is high (Moejes & Moejes 2017; Muñoz & Gonzalez-Fernandez 2017). These problems can vastly decrease production rate efficiency. Third, although they require low capital costs, it is more expensive to harvest algae from raceway ponds than from tubular PBRs due to their inefficiency and low biomass density, between 0.1 and 0.5 g/L (Moejes & Moejes 2017; Muñoz & Gonzalez-Fernandez 2017).

Consequently, closed-air cultivation systems, such as tubular, column, flat, flat panel airlift, and plastic bags, are being established to have better control over the operating conditions and improved quality, and produce high value added products for pharmaceutical applications (Acien et al. 2017). In fact, microalgae PBRs are gaining increased commercial interest due to their widely acclaimed industrial benefits: (1) they are feasible in culturing and harvesting

products; (2) they have low contamination; (3) they have high biomass productivity – generally between 0.5 and 8 g/L (Moejes & Moejes 2017); (4) they require a smaller area than traditional crops when grown in photobioreactors; and (5) there is prevention of water loss caused by evaporation (Xu *et al.* 2009; Huang *et al.* 2017). However, PBRs require a high capital cost (Moejes & Moejes 2017). Their operating cost is high as they require proper mixing, and the perpetual cleaning of the vessels. The downstream process for both closed and open PBRs is still expensive.

Design factors of PBRs

There are several factors that must be considered besides the capital costs and operating costs. When designing a PBR shape or size or volume, the light distribution, mixing, mass transfer, and abiotic conditions, along with the growth kinetics of the algae, are all factors that must be taken into account (Huang *et al.* 2017; Placzek *et al.* 2017). Thus, this section aims to break down these factors while elaborating on their respective conditions that must meet the algae growth requirements.

Light

Besides availability, there are three important variables of light that must be considered to ensure proper photosynthesis: spectral quality, light intensity and photoperiod (Pattanaik *et al.* 2018). PBRs may be employed indoors or outdoors. In the case of outdoors, natural solar radiation is the light source. It is free and plentiful, so it is usually employed for mass cultivation. Solar radiation covers a wide spectral range, but microalgae make use of the light that falls between 400 and 700 nm (Huang *et al.* 2017). This range is known as the photosynthetic active radiation (PAR). PAR accounts for only 50% of the sunlight spectra, radiance falling outside this range is converted to heat energy which warms up the PBR or is lethal to cells if they lie within the ultraviolet range. Moreover, to ensure all microalgae absorb light equally, the PBR surface to volume ratio must be considered (Huang *et al.* 2017; Moejes & Moejes 2017). This is because light intensity decreases almost exponentially with distance away from the illuminated surface of the PBR. However, microalgae do not require an enormous amount of light

intensity to carry out photosynthesis (Moejes & Moejes 2017). In fact, oxygenic photosynthetic organisms can reach a maximum theoretical conversion efficiency of 8–10% solar-to-biomass energy (Posten 2009; Moejes & Moejes 2017).

Photoinhibition will take place if the light intensity surpasses the saturation level (the light saturation intensity), and the growth of the algae will be inhibited. Light radiated will be wasted first as fluorescent then as heat. At the same time, if the light intensity is below that required to maintain photosynthesis (the light maintenance point), the growth would be limited, i.e. photolimitation occurs, and the culture would collapse. The range at which light intensity is needed for photosynthesis to take place varies slightly from one species to another. Another final aspect is the photoperiod. Dark hours are important for the algae to carry out respiration to retain the energy needed to carry out photosynthesis. Accordingly, the optimum period of illumination is between 12 and 15 h (Posten 2009). This period, however, is interchangeable outdoors depending on the weather.

In the case of outdoor cultivation, it is preferred to orient the PBRs in the west/east direction as it yields 1.4 times biomass more than those oriented in the north/south direction (Huang *et al.* 2017). This only applies to regions in the Northern Hemisphere. In the case of indoors, it is advisable to use an LED lighting system that is designed to emit wavelength within the PAR, for 12–15 h. Also, an unusable wavelength spectrum can be eliminated by adjusting the power supply which in fact lowers the LED power consumption (Pattanaik *et al.* 2018). Additionally, LED lighting systems also produce the same lighting intensity as fluorescent lights but consume less than half of the electric energy used (Narukawa *et al.* 2006). They are small, lightweight, durable, easy to install, and do not produce that much heat compared to other light sources (Koc *et al.* 2013). Moreover, it was found that using red LED lighting produces the highest number of cells with the highest biomass productivity while blue LED lighting produces larger cells, i.e. larger in diameter and rounder (Koc *et al.* 2013). So, another approach to cultivating algae was to initially use a red LED to produce the desired cell concentration, then switch to blue light to increase cell size (Shu *et al.* 2012; Koc *et al.* 2013). Another tip to increase the light flux received by the PBR is to attach a reflecting mirror or paint the ground white material at the back of or under the PBR (if they are tubes) (Abu-Ghosh *et al.* 2015;

Placzek *et al.* 2017). This is to increase the light reflection by creating a continuous weak light background which increases the biomass (Abu-Ghosh *et al.* 2015).

Temperature

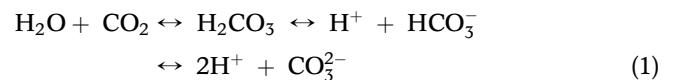
Microalgae can grow at temperature ranges between 15 and 35 °C (Ras *et al.* 2013). Temperatures lower than 16 °C lower the growth rate of the cells while temperatures higher than 35 °C kill the microalgae cells (Bitog *et al.* 2011). The optimal temperature for culturing is between 20 and 25 °C (Bitog *et al.* 2011; Pattanaik *et al.* 2018). A PBR is subjected to a significant variation of temperature due to seasonal changes, especially if it is placed outdoors (Huang *et al.* 2017). Without temperature controlling systems, temperatures could vary from 10 to 30 °C from where it started (Wang *et al.* 2012). The disruptions in temperature make the cultivation inefficient. Thus, a temperature control system is needed to maintain a favorable temperature.

For an open PBR system, especially those constructed in desert areas where the temperature could rise more than 40 °C, the temperature could be controlled easily if it is already constructed in a greenhouse. On the other hand, there are several methods to control the temperature in the closed PBR system. First, installing sprayers on the top of the PBR that spray water when the reactor exceeds the limiting temperature enables cooling by evaporation and decreasing the temperature when needed (Wasanasathian & Peng 2007); this is a good method for cooling but costly as a huge amount of water is needed to be pumped and sprayed from above. Second, partially or completely submerging the culture into a pool of water; this is an affordable method and has demonstrated that it could increase the average light intensity in the part that is submerged in the water (Carlozzi *et al.* 2006). Third, use dark sheets that serve as shading the PBR that decreases the solar radiation and increases the accumulation of total chlorophyll and carotenoids which increases the biomass productivity (Ugwu & Aoyagi 2008); this is the cheapest yet most inefficient method as it reduces the light intensity. Finally, there are other heat exchange methods such as overlapping the warm tubes with cool ones or regulating the temperature of the feed (Singh & Sharma 2012).

pH

Cellular processes inside the algae are pH sensitive. Microalgae prefer to culture in a media that has a pH between 8.2 and 8.9 but they tolerate pH ranges between 7 and 9 (Berberoglu *et al.* 2008). So, pH ranges outside these parameters cause a breakdown to the culture due to the disruption of cellular processes inside the microalgae. There are also species with extreme abiotic conditions (high temperature, salinity, etc.), also known as extremophiles (Wang *et al.* 2012).

The pH of culture is affected by the presence of CO₂. The solubility of CO₂ is relatively low; 1,650 ppm at 25 °C in pure water (Vasumathi *et al.* 2012). Absorption of CO₂ in water is important for the cultivation of microalgae and it acts as a buffering system due to dissolution equilibrium of CO₂:



In freshwater, when the pH is 6.5, equal proportions of the CO₂ and bicarbonate (HCO₃⁻) form. At pH 8.3, nearly all inorganic carbon is in bicarbonate form. At that point, the bicarbonate dissociates into carbonate (CO₃²⁻) until equal proportions form bringing the pH to 10.4. When almost all the inorganic carbon is in carbonate ion form, the pH is 12.

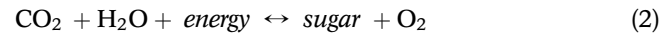
When microalgae carry out photosynthesis by consuming CO₂, the chemical equilibrium shifts towards the left, increasing the pH. Although a high pH level is not favorable, most microalgae species can take up CO₂ in the form of bicarbonate (Sayre 2010). Therefore, substances such as HCl or sodium bicarbonate may be added to control the culture pH and keep it from rising too quickly (Granum 2002).

Mass transfer (gas exchange)

There are three chemical processes that take place during the growth of microalgae: photosynthesis, photorespiration, and dark respiration (Wang *et al.* 2012). Each of these processes requires a different gas exchange rate. It is known that microalgae consume CO₂ during photosynthesis. Looking inside the microalgae, the CO₂ is fixed by rubisco enzyme (ribulose biphosphate carboxylase oxygenase) to

produce two molecules of 3-phosphoglycerate (Sayre 2010). As this process proceeds, oxygen is produced. The non-removal of oxygen from the culture causes two problems. First, the presence of oxygen acts as a competitive inhibitor of CO₂ fixation by rubisco. As the oxygen is consumed, CO₂ is lost which is necessary to regenerate the five-carbon sugar substrate ribulose biphosphate – required for CO₂ fixation by rubisco – hence mitigating the photosynthesis process (Sayre 2010). This process is called photorespiration and it can reduce photosynthesis efficiency by 20–30% (Zhu et al. 2008). Second, oxygen concentrations above air saturation decrease photosynthesis efficiency in microalgae (Aiba 1982; Kazbar et al. 2019). In a PBR, the dissolved oxygen concentration level in water is influenced mainly by temperature and photosynthesis. It is known that an increase in water temperature lowers the solubility of oxygen in water. However, due to the non-ideal equilibrium conditions between air and water, the equilibration (or equalization) of the oxygen content of water with the air is a slow process except when the system is highly agitated (Higgins 2014). So, at 20 °C, the maximum amount of DO the water can dissolve is 9.03 mg/L (Czuba et al. 2011). This value corresponds to the 100% air saturation which is the equilibrium point for gases in water since gas molecules diffuse between the atmosphere and the water's surface. If the temperature is increased to 22 °C, which can be rapidly achieved, the maximum amount of DO the water can dissolve decreases to 8.22 mg/L. If the water is stagnant or there is an absence of an efficient agitator, the equilibration process of oxygen is slowed so the DO in water would not immediately decrease from 9.03 to 8.22 mg/L, hence it will be in $(9.03/8.22 \times 100)$ 110% air-saturation. This is the point where the photosynthesis efficiency decreases (Carvalho et al. 2008; Peng et al. 2013). Several studies reported the inhibitory effects of oxygen to microalgae growth at high concentrations. For instance, Raso et al. (2011) reported a linear decrease in specific growth rate of *Nannochloropsis* sp. from $0.48 \pm 0.40 \text{ d}^{-1}$ at a DO of $4.95 \text{ mg O}_2 \text{ L}^{-1}$ (75% air saturation at 25 °C) to $0.18 \pm 0.01 \text{ d}^{-1}$ at $16.5 \text{ mg O}_2 \text{ L}^{-1}$ (250% of air saturation at 25 °C). Molina et al. (2001) stated that the photosynthesis rate of *Phaeodactylum tricornutum* decreased from $0.0036 \text{ mol O}_2 \text{ m}^{-3} \text{ s}^{-1}$ at $9.1 \text{ mg O}_2 \text{ L}^{-1}$ (100% of air saturation at 20 °C) to $0.0016 \text{ mol O}_2 \text{ m}^{-3} \text{ s}^{-1}$ (55% reduction) at the DO of 43.23 mg L^{-1} (475% air saturation at 20 °C).

To explain this, the photosynthesis chemical reaction is as follows:



As dissolved oxygen (DO) builds up in the media from the photosynthesis of microalgae and is not removed, given the media is at constant temperature, and due to poor mixing techniques and low mass transfer rates, the concentration of DO in the media increases. When the DO concentration exceeds 100% air the reversible reaction is shifted to the left, decreasing photosynthetic efficiency (Carvalho et al. 2008).

The CO₂ is considered the carbon source needed for microalgae to carry out photosynthesis. However, it can only be consumed in liquid form, i.e. CO₂ needs to be absorbed by the medium, to be fixed by rubisco. Therefore, the dissolved carbon dioxide (DCD) is the consequence of the balance between the consumption of CO₂ by the microalgae cells and the CO₂ mass transfer from the gas phase to the liquid phase. To increase the DCD levels in water, the surface area for mass transfer from gas to liquid phase can be increased through either direct bubbling or absorption in packed beds.

Supplying CO₂ through bubbling has been studied by many researchers. According to Henry's Law, as the concentration of CO₂ increases in the air supplied, it would result in a proportional increase in dissolved CO₂ concentration in the aqueous phase (Mook 2008). This law was demonstrated by Hill et al. (2006), where 10% CO₂ by volume in the gas phase resulted in a total of 150 mg/L of DCD while for air containing only 0.037% by volume of CO₂ in gas phase resulted in 0.7 mg/L of DCD. Hence, it is recommended to directly bubble pure CO₂ also because the bubbles increase the surface area of contact between air and water. However, a major disadvantage of direct bubbling is that it could cause shear stress over the biomass particles which could damage it and it has high power consumption (Vasumathi et al. 2012). Another method of increasing DCD in water is by using the packed bed absorption column. This is where the gas phase is fed in a countercurrent manner against the medium flow inside a column. Just like the bubbling method, it is an even more power consuming application due to the energy needed to overcome the pressure drop in a bed (Vasumathi et al. 2012). In conclusion, the best

criterion for the gas supply method is one where it consumes as little power as possible, has maximum surface area per unit volume of water, and does not induce cell damage.

Although there are several ways to supply CO₂, there are two abiotic factors that increase the desorption rate (Vasumathi *et al.* 2012). First, blowing of wind (in the case of outdoor cultivation). Second, increasing the water medium temperature will reduce the CO₂ solubility. To increase the absorption rate and retention of CO₂ in water, one method is to use an alkaline solution where CO₂ is being absorbed as carbonate or bicarbonate (Wang *et al.* 2008). In fact, microalgae with carbonic anhydrase enzymes are capable of better utilizing carbonate and converting it to CO₂ to facilitate CO₂ assimilation (Wang *et al.* 2008).

Another aspect worth mentioning is the quality of the air supplied to the medium. Supplying pure CO₂ proves to be better than supplying air as the DCD level would differ greatly. However, supplying flue gas from thermal power plants has proven to increase biomass productivity by 30% compared with direct injection of an equivalent concentration of pure CO₂ (Douskova *et al.* 2009). This is not only because flue gases have high CO₂ concentration, but also because of the lower partial pressure of O₂ in the flue gas compared to the conventional air supply reducing the phenomena of photorespiration and photoinhibition (Douskova *et al.* 2009). Flue gas from municipal waste incinerators (Douskova *et al.* 2009), coal-fired power plants (McGinn *et al.* 2011), industrial heaters using kerosene as fuel (Chae *et al.* 2006), and gas boilers (Doucha *et al.* 2005) have all been used for cultivation. Flue gases, however, whether they are untreated or not, contain pollutants (NO_x, SO_x, C_xH_y, CO, halogen acids, particulate matters, and heavy metals) and are high in temperature which could impose a threat on the microalgae growth and their toxicity (Van Den Hende *et al.* 2012). Fortunately, there is progress on isolating *Chlorella* sp. mutants that would tolerate high levels of NO_x and SO_x in flue gases (Chiu *et al.* 2011) as well as high temperatures (Chou *et al.* 2019). Moreover, according to Douskova *et al.* (2009), the toxicological analysis carried out on the microalgae cultivated using untreated flue gas from municipal waste incinerators has shown that while there was high mercury levels, other critical compounds were below the limits recommended by the European Union food-stuff legislation. To conclude, there is a need for research on

the influence of these pollutants on the biomass of microalgae while searching for solutions to minimize the pollutants.

Mixing

Perpetual mixing inside the PBR has proved to considerably enhance the productivity of the biomass (Acién *et al.* 2013). Mixing basically ensures (Wang *et al.* 2012; Acién *et al.* 2013; Abu-Ghosh *et al.* 2016):

1. Uniform light and nutrient distribution
2. Improved gas exchange between the culture medium and the air phase
3. Prevention of microalgae sedimentation
4. Avoidance of cell attachment to the reactor wall
5. Facilitation of heat transfer and avoidance of thermal stratification.

However, if not done with caution mixing can cause cell damage if the microalgae are susceptible to shear stress (Acién *et al.* 2013). Accordingly, it was found that liquid velocity exceeding 100 cm/s would produce micro eddies (with diameters less than 50 micrometers) which would induce cell damage (Posten 2009). Therefore, liquid velocities must not exceed 20–50 cm/s (Posten 2009). Mixing can be carried out by mechanical agitation using an impeller, by aeration by directly pumping CO₂-enriched gas bubbles, or using a combination of both methods, all of which depends on the type of reactor.

Mixing also brings about light/dark (L/D) cycle known as the flashing light effect (FLE) which could enhance photosynthesis and improve the quality and quantity of the products (Fathurrahman *et al.* 2013; Abu-Ghosh *et al.* 2016; Martín-Girela *et al.* 2017). FLE is when the microalgae cells, as a result of mixing, perpetually move from saturated light (near the surface of the reactor/pond) to darker zones (middle of the reactor/bottom of the pond), hence, cells are being subjected to 'flashing-light'. Inducing FLE in an outdoor microalga open pond can be done by adjusting the mixing velocity of the culture. For indoor PBR, FLE can be done by adjusting the circulating velocity or bubbling rate and by using shading to make it simpler (Abu-Ghosh *et al.* 2016). Accordingly it was found that biomass productivity of green microalgae *Nannochloropsis salina* increased more than 55% when the frequency of the L/D

cycles was set at 60 Hz (Iluz & Abu-Ghosh 2016). Moreover, there are other studies that found FLE to be successful (Fathurrahman et al. 2013; Martín-Girela et al. 2017). However, several experiments conducted have concluded that the production of microalgae was decreased when the L/D cycle or the frequency of the flashes was not optimized (Sforza et al. 2012; Vejrazka et al. 2012, 2015). For example, according to Vejrazka et al. (2012), L/D cycles below 10 Hz decreased the biomass yield by 10% on average while setting at a frequency of 100 Hz the biomass yield increased by 35% on average. Most recently, Schulze et al. (2020) showed that the FLE inhibited growth of green microalgae *T. chui* and *C. stigmatophora* cultures. In general, there are no common conclusions obtained about the effect of FLE. This technique needs to be developed and experimented on several species to conclude whether it is suitable for all species and the optimum FLE frequency.

Nutrients

Different microalgae species utilize different sources of energy to proceed with their growth. Not all microalgae are photoautotroph. In fact, they are split into two major groups: autotrophs and heterotrophs. Autotrophs rely on converting solar radiation and CO₂ absorbed by chloroplasts into adenosine triphosphate (ATP) and O₂ while heterotrophs consume organic carbon produced by other organisms, as they cannot produce their own food, to satisfy their material and energy needs. A third and final group is mixotrophic which combines both chemical pathways to achieve growth. Table A2 summarizes the types of autotrophs and heterotrophs.

It is essential to have a carbon source alongside main macro-nutrient nitrogen (N), potassium (K), and phosphate (P). Other elements that need to be present include calcium (Ca), magnesium (Mg), and trace elements such as copper (Cu), manganese (Mn), selenium (Se), or zinc (Zn), which are needed for enzyme functions (Placzek et al. 2017).

Macro-nutrients can be obtained from commercial chemical grades (Geada et al. 2017). Globally, there is an abundance in potassium and phosphate mines. The trace elements may or may not need to be added because they are required in very small amounts and could already be present in the freshwater or seawater source. Pharmaceutical-based cultivated microalgae require extremely pure chemicals which are expensive.

Recently, there is an increasing use of wastewater as the culture medium while bioremediating them. This approach is more environmentally sustainable and cost-effective. With the combination of flue gas, this way of cultivation has proven to be a significant approach that can tackle environmental issues (Mata et al. 2010). The wastewater used as a culture medium can be derived from livestock, food industries, and even municipalities (Geada et al. 2017). These waste streams contain a high source of organic carbon content that represents 80% of the entire medium cost which can be used to cultivate mixotrophic and heterotrophic microalgae. Table 2 summarizes the findings of the general parameters for microalgae cultivation.

Statistical properties for macroalgae cultivation

There are several studies designed for better understanding of optimization conditions and parameters with a lower number of experiments through utilizing different statistical tools (Eris et al. 2018). The most popular tool for microalgae cultivation that has been used during the recent publications is response surface methodology (RSM) based on central composite design (CCD) (Skorupskaitė et al. 2015). The statistical analysis of this methodology was conducted using the analysis of variance (ANOVA). ANOVA determines the statistical difference of the independent variables (Wang et al. 2019). Table 3 summarizes four research outcomes that used the RSM and CCD for the optimization parameters of different microalgae species. First and second order multiple polynomial models are developed based on the investigation of independent variables regions (Mohamed et al. 2015; Chellamboli & Perumalsamy 2014; Skorupskaitė et al. 2015; Wang et al. 2019). Statistical properties of the developed models that are presented in Table 3 give adequate information about the significance, accuracy, and

Table 2 | Summary of design parameters for microalgae cultivation

Parameter	Value	Unit
Light illumination time	12–15	h
Light spectral range	400–700	nm
Temperature	20–25	°C
pH	8.2–8.9	–
Liquid velocity	20–50	cm/s

Table 3 | Brief statistical properties parameters for different optimization conditions of microalgae cultivation

Reference	Statistical properties model						Independent variables				Dependent variable	Regression equation	
	P Value	F value	R ²	R _{adj} ²	Mean Square	Lack of fit	df	X ₁	X ₂	X ₃	X ₄		Y
a	0.0079	-	0.924	0.848	-	0.518	-	Nitrogen concentration (g/L)	Technical glycerol concentration (g/L)	Amount of salts (g)	-	Conc. of biomass (g/L)	$Y = 1.67 - 0.1 X_1 - 0.21 X_2 - 0.058 X_3 - 0.091 X_1 X_2 - 0.063 X_1 X_3 + 0.0058 X_2 X_3 + 0.12 X_1^2 + 0.025 X_2^2 + 0.04 X_3^2$
b	<0.0001	22.81	0.953	0.912	$3.726 * 10^{-7}$	5	9	Culture time (d)	Inoculum (%)	Sodium bicarbonate (g/L)	-	Growth rate (g/L.d)	$Y = 0.037875 - 4.00297 * 10^{-6} X_1 - 9.71294 * 10^{-5} X_2 + 7.95287 X_3 + 1.34286 * 10^{-6} X_1 X_2 + 2 * 10^{-6} X_1 X_3 - 5.36 * 10^{-6} X_2 X_3 + 7.07236 * 10^{-7} X_1^2 + 9.41364 * 10^{-6} X_2^2 - 5.04727 * 10^{-6} X_3^2$
C	<.0001	89.89	0.988	-	$6.94 * 10^{-3}$	$6.08 * 10^{-4}$	14	Nitrate (g/L)	Bicarbonate (g/L)	Phosphate (g/L)	Magnesium sulphate (g/L)	Biomass (g/L)	$Y = 1.20 + 0.40 X_1 + 5.26 X_2 + 2.24 X_3 + 2.01 X_4 - 0.08 X_1 X_2 + 0.42 X_1 X_3 - 0.13 X_1 X_4 + 2.78 X_2 X_3 + 1.51E - 013 X_2 X_4 + 1.49E - 013 X_3 * X_4 - 0.18 X_1^2 - 37.96 X_2^2 - 25.46 X_3^2 - 7.16 * X_4^2$
d	0.0003	14.2	-	0.868	12.84	6.21	9	Glucose (g/L)	Yeast extract (g/L)	Sodium Nitrate (g/L)	-	Biomass conc.(g/L)	$Y = -20.02 + 0.85 X_1 + 6.26 X_2 + 4.5 X_3 - 0.015 X_1^2 - 1.00 X_2^2 - 0.5 X_3^2 + 0.025 X_1 X_2 + 0.052 X_1 X_3 - 0.375 X_2 X_3$

^aSkorupskaite *et al.* (2015); ^bChellamboli & Perumalsamy (2014); ^cWang *et al.* (2019); ^dMohamed *et al.* (2013).

reliability of each equation. Also, average reported values gathered from many references are presented in Figures 3 and 4 to visually illustrate the effect of temperature, time and sodium bicarbonate on the microalgae cultivation presented in the biomass (Chellamboli & Perumalsamy 2014; Munir et al. 2015; Wang et al. 2019).

TYPE OF PBRs

PBRs can be categorized into two main groups: open PBRs and closed PBRs. Under each category comes a subcategory that could be based on the PBRs shape, agitation mode (if any), mechanical parts etc. Figure 5 illustrates the subcategories in open and closed PBRs. In general, open PBRs are much simpler in their design than closed PBRs as it is only required to choose the shape of the reactor based on

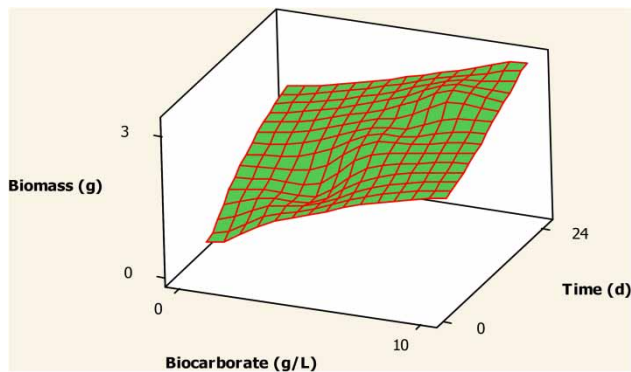


Figure 3 | Plot of average optimization values for biomass, bicarbonate, and time. Adapted from Chellamboli & Perumalsamy (2014), Wang et al. (2019) and Munir et al. (2015).

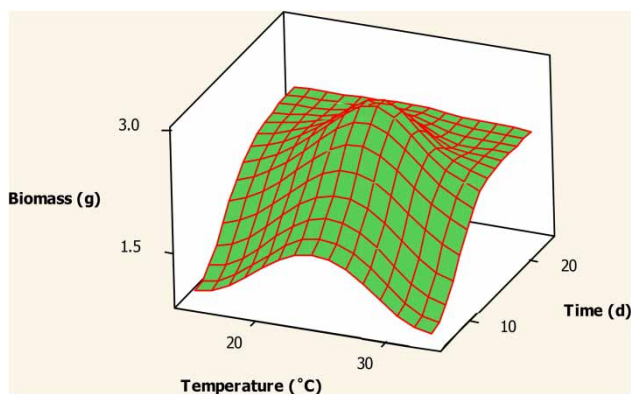


Figure 4 | Plot of average optimization values for biomass, temperature, and time. Adapted from Chellamboli & Perumalsamy (2014), Wang et al. (2019) and Munir et al. (2015).

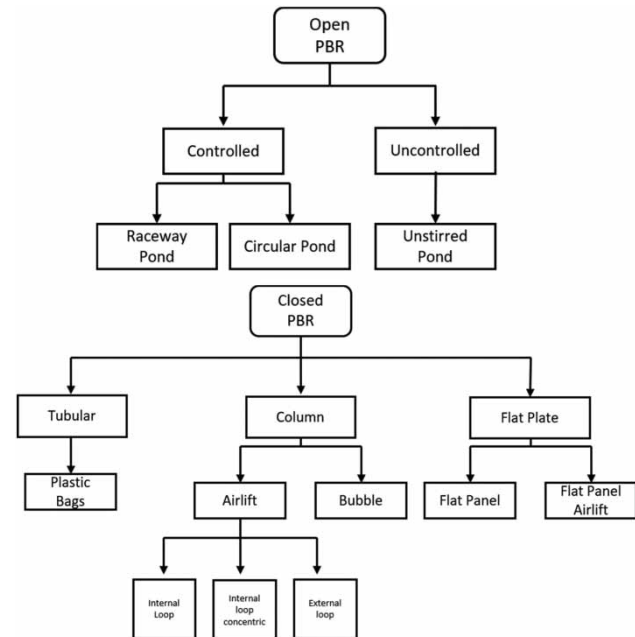


Figure 5 | Subcategories of PBRs.

the available area. For open PBRs the main differences lie in the flow of the culture, i.e. stirred or unstirred. For closed PBRs the subcategories have different features as some are more robust, others have better surface/volume ratio, and some are economically more feasible than others. Figure 6 demonstrates the different types of closed and open PBRs. Tables 4 and 5 summarize the design criteria, advantages, disadvantages, and applicability for household scale for open and closed PBRs.

DOWNSTREAM PROCESSING

Methods of harvesting

After the process of cultivation, the biomass is separated from the bulk medium and recovered as part of the downstream process. Harvesting involves two steps:

- (1) *Primary harvesting or bulk harvesting*, where the microalgae are separated from their growth medium. The total solid mass can reach up to 2–7% using flocculation, flotation, or gravity sedimentation (Brennan & Owende 2010).
- (2) *Secondary dewatering or thickening*, where the microalgae slurry is concentrated typically by centrifugation or

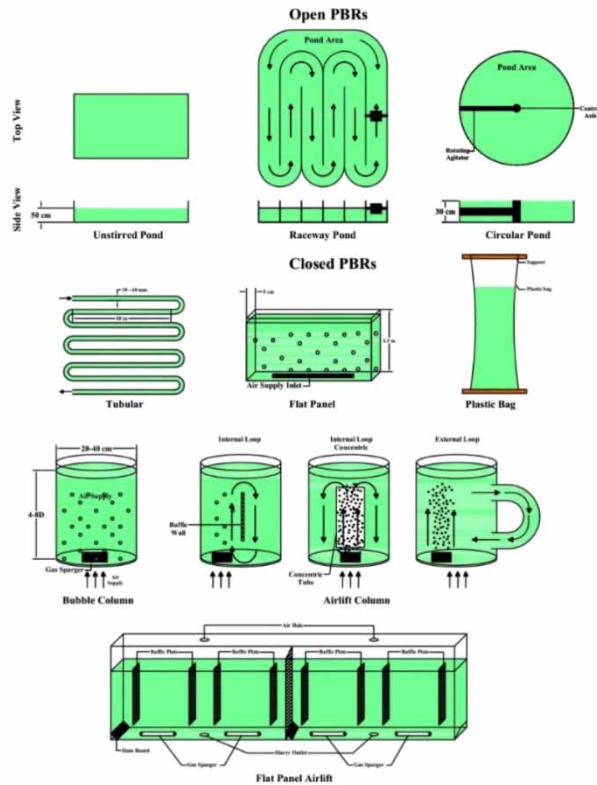


Figure 6 | Schematic diagram of open and closed PBRs.

filtration (Lam & Lee 2012). The total solid mass can reach 15–25%. This step requires more energy.

Harvesting techniques depend on the physiology of the microalgae species, the density, the preferred end-product and the possibility of reusing the medium once again (Borowitzka & Moheimani 2012). This section discusses the suitability of each method to be used on household scale.

Primary harvesting

Flocculation is a process in which the dispersed particles are aggregated together to form large particles for settling. In the culture medium, flocculants are added to neutralize the negative charged microalgae so it could eventually slowly settle by sedimentation. There is autoflocculation, chemical flocculation, electroflocculation and, bio-flocculation.

Autoflocculation occurs naturally due to changes in environmental factors such as nitrogen levels, pH and dissolved oxygen levels (Uduman et al. 2010). The floc is mediated by gravity and absence of light. Electroflocculation

is a method where electric rods connected to an electric field are immersed into the culture medium to: (1) generate coagulants by electrolytic oxidation of the sacrificial electrode followed by (2) destabilizing the microalgae suspension eventually forming flocs. This method is commonly used in the removal of microalgae from industrial wastewater (Azarian et al. 2007). This process has an efficiency of 80–95% of microalgae removal (Chen et al. 2011). The efficiency of this process depends on the electrode material, electrolysis time, current density, pH and composition of the microalgae suspension. Aluminum rods are the most suitable electrode material (Lee et al. 2013; Dassey & Theegala 2014). Electroflocculation and flotation are used in conjunction (Chen et al. 2015).

Bioflocculation is when microorganisms produce bio-flocculants which flocculate the algae. These bio-flocculants could be the organic matter produced during the algae growth which are known as extracellular polymeric substances (EPS). EPS may also be produced by the bacteria added as an organic carbon source or even fungi. For example, Wan et al. (2013) harvested *Nannochloropsis oceanica* using bioflocculant from the bacteria strain *Solibacillus silvestris* with 90% efficiency. Similarly, Zhou et al. (2013) and Xie et al. (2013) have used fungi to harvest *Chlorella vulgaris*. Table 6 compares the advantages and disadvantages between the aforementioned flocculation.

Chemical flocculation is the addition of chemicals to induce flocculation. These chemicals may be from organic or inorganic sources. Table 7 enlists the different types of chemical coagulants used, their optimal dosage, and optimal pH.

From this classification, it is easy to say that autoflocculation is the simplest and cheapest type of flocculation which can be applicable at household level and does not require expertise or knowledge. Simply, at the end of the growth stage, the aerator will be switched or the PBR can be covered to simulate autoflocculation. Electroflocculation is a more efficient, quicker and also affordable solution but it requires sufficient knowledge about the mechanism, which can be passed along by the local manufacturer. Finally, biochemical flocculation is costly and contaminates the microalgae making it inconvenient as feed which makes it the least favorable choice in terms of flocculation at the household level.

Table 4 | Types of open PBRs (Shen et al. 2009; Geada et al. 2017; Ting et al. 2017)

Type	Design features	Advantages	Disadvantages	Example of application	Household applicability
Unstirred ponds	<ol style="list-style-type: none"> 1. Natural water systems without any mechanical mixing 2. Less than 0.5 m in depth to allow full light penetration 3. Plastic films can be used to cover the surface of water for a better temperature control. 4. <i>Dunaliella salina</i> is a fit species to be cultured in these types of pond 	<ol style="list-style-type: none"> 1. Simple construction 2. Low energy consumption 3. Microalgae inside can withstand poor conditions and outgrow contaminants 4. Easy to scale-up 	<ol style="list-style-type: none"> 1. Poor mass and heat transfer 2. Limited to certain type of robust microalgae 3. Low productivity 4. Difficult to be controlled 	Betatene Ltd for β -carotene production in Australia	<p>These ponds are easy to operate and construct, and cheap in comparison to other types. Their yield, however, is very low and they are susceptible to contamination. Therefore, they can serve as soil conditioner and air purifier but it is not advisable to use the yield for human or animal feed supplement</p> <p>Applicability rating: Low</p>
Raceway ponds	<ol style="list-style-type: none"> 1. Closed loop, oval shaped recirculation channels 2. Between 0.15 and 0.3 m deep 3. Built in concrete, glass fiber reinforced plastic, metal sheet 4. A paddlewheel is included to prevent biomass sedimentation and increase biomass growth 5. CO₂ may be supplied by submerged aerators 6. Can be construction under a greenhouse to ease the control of the operating conditions 	<ol style="list-style-type: none"> 1. Better mixing of nutrients and distribution of heat 2. Easy scale-up 3. Higher productivity than unstirred pond 	<ol style="list-style-type: none"> 1. Paddles are susceptible to mechanical damage 	Raceway ponds in Earthrise farms, 440,000 m ² in California, USA (<i>Spirulina</i>) Parry Agro Industries (India)	<p>Raceway ponds require a reasonable area to yield a threshold profitable amount. They have more expensive capital and operational costs than unstirred ponds and they are also susceptible to contamination if not placed under a greenhouse. They definitely yield more microalgae than unstirred ponds and the harvest can be sold for medical uses and human feed. So, their return is much greater than unstirred ponds</p> <p>Applicability rating: Medium</p>
Circular ponds	<ol style="list-style-type: none"> 1. Area must not exceed 10,000 m² (due to mechanical restrictions) with depth of 0.3 m 2. Mixing is done by central rotating agitator 3. Built using concrete, glass fiber reinforced plastic, metal sheet 4. A velocity of 10–20 cm/s was found effective 	<ol style="list-style-type: none"> 1. Better mixing of nutrients and distribution of heat 	<ol style="list-style-type: none"> 1. Limited by its diameter, poor mixing efficiency when the rotating arm gets too long (>50 m) 	Circular ponds in Yaeyama, Japan (<i>Chlorella</i>)	<p>Like raceway ponds, but operational costs may be more expensive as the central rotating agitator would consume more power than a paddlewheel</p> <p>Applicability rating: Medium</p>

Table 5 | Types of closed PBR (Wang et al. 2012; Gupta et al. 2015; Geada et al. 2017; Huang et al. 2017; Placzek et al. 2017)

PBR Type	Design feature	Mixing	Gas exchange	Temperature control	Advantages	Disadvantages	Examples of applicability	Household applicability
Tubular	<ol style="list-style-type: none"> There are three main structures/shapes of this type: Helical, Serpentine, α-shaped Glass or plastic tubes are usually used as materials for construction Can be oriented horizontal, inclined, vertical, or helical The microalgae culture is circulated by a pump or by aeration systems. Liquid velocities range from 0.2 to 0.5 m/s must be within the range 2400–3200 W m⁻³ Diameters of the tube between 10 and 60 mm The length of a straight pipe section in such installations cannot exceed 80 m. Total length can be several hundred meters High surface to volume ratio (above 100/m) 	Pumps	Injection into feed, dedicated degassing unit	Shading or overlapping, water spraying	<ul style="list-style-type: none"> Great illumination surface area Suitable for outdoor cultures Good biomass productivities 	<ul style="list-style-type: none"> Photoinhibition occurs with large diameters. CO₂, O₂, and pH gradients develop with long tubes Large land surface occupation Difficult temperature control as it need continuous measurements to measure and control Fouling and foaming formation Cleaning is done mechanically 	25 m ³ plant from Mera Pharmaceuticals, Hawaii (USA) 700 m ³ (500 km long total) plant located nearby Wolfsburg (Germany) 600 km glass tubes, AlgaTechnologies, Israel	Complicated design, high operational cost and hence high capital cost is needed. The cleaning is difficult. Applicability rating: Low
Column	<ol style="list-style-type: none"> There are two types: bubble and airlift Airlift has three orientations: internal loop, internal loop concentric, external loop Transparent glass or plastic cylinders with height up to 4 m Diameter 0.2 m (recommended to obtain enough light) up to 0.4 m Flashing light effects can be achieved in the airlift PBR. The ratio of the height to the diameter is in the range from 4 to 8. Geometrical condition $H > 2D$ is fulfilled. The pump is within the range 40–50 W m⁻³ 	<ol style="list-style-type: none"> Bubble PBRs: Gas sparger Airlift PBRs: Gas sparger with interconnecting zones the riser (up flowing) and the downcomer (down-flowing) streams which create a uniform circulation 	Open gas exchange at headspace	Shading of columns	<ul style="list-style-type: none"> Low operating cost and low power consumption Suitable for outdoor and indoor cultivation Efficient homogenous mixing in airlift PBRs due to swirling flows Low shear stress, low photoinhibition^a Easy to sterilize High photosynthetic efficiency when increasing the gas feed rate 	<ul style="list-style-type: none"> Low illumination surface area High CAPEX^b and OMEX^c Difficult to control the temperature Limited scale up due to design constraints, shading effect issues 	Sea and Sun Technology, Heinz Schelwat, Germany	This is the simplest type of closed PBR, in specific, bubble column. The shape can be easily cut out at any local contractor. The components required are applicable and overall, not an expensive capital/operational costs. Applicability rating: High

(continued)

Table 5 | continued

PBR Type	Design feature	Mixing	Gas exchange	Temperature control	Advantages	Disadvantages	Examples of applicability	Household applicability
	<p>8. Not suitable for algae cultivation with a low specific weight</p> <p>9. For airlift (i) internal loop setup, an internal baffle is placed to separate the riser and downcomer. For (ii) internal loop concentric setup, air is sparged into a concentric tube</p>							
Flat panel	<p>1. They are made alveolar panels or glass plates</p> <p>2. A frame covered by a 16 mm thick transparent plate (glass, plexi-glass, polycarbonate) on both sides</p> <p>3. A pump is used to circulate the algal cell suspension. A pump with 53 W m^{-3}</p> <p>4. Surface/volume ratio around $400 \text{ m}^2 \text{ m}^{-3}$ is recommended</p> <p>5. The bioreactor surface to the area of the plot which is occupied by the cultivation should be equal to at least 10</p>	Airlift/bubble from bottoms or side (1 liter of air per 1 liter of reactor volume per 1 minute)	Open gas exchange at headspace	Heat exchange coils, or partially immersed in water pool	<p>High surface to volume ratio</p> <p>high photosynthetic efficiencies</p> <p>High biomass concentration up to 80 g/L</p> <p>Reduced power consumption</p>	<p>Not recommended for commercial-scale production due to requirements of many compartments</p> <p>Biofouling on surface</p> <p>High-stress damage of cells associated with aeration</p> <p>Sterilization issues</p> <p>Difficult temperature control</p>	110 L Green Wall Panel PBRs located at Livorno, Italy	<p>Similar to the bubble column reactor but only differs in shape which is not complicated as well. This, however, can yield more microalgae per m^3 and does not occupy much space.</p> <p>Applicability rating: Medium</p>
Plastic bags PBRs	<p>1. Polyethylene bags that are hung vertically individually or in the form of a parallel series of bags mounted on support (rack)</p> <p>2. A circulation pump is used to drive the flow of liquid and feed air</p>	Via aeration system	Gas feed into the bags	Immersed in a water pool	<p>Low operating cost and low power consumption</p> <p>Good surface to volume ratio</p>	<p>Photo limitation commonly occurs due to distortion of the bags by gravity</p> <p>Poor mixing</p> <p>Dead zones at certain parts of the bag</p> <p>Leakage happens more than occasionally</p> <p>Short lifespan</p>	Commercial scale plastic-bag PBR, Solix. Colorado, USA	<p>The cheapest kind of closed bioreactor that local farmers can easily afford. It is easy to construct but is subjected to leaks and bursts and on top of that.</p> <p>Applicability rating: High</p>

Flat-panel airlift reactor combines the airlift reactor swirling loop concept with a flat-panel shape reactor

Induced by the well-defined circular flow

Open gas exchange at headspace

Water sprayers on the irradiated surface or submerging the bottom of the PBR in a water pool

High surface to volume ratio

High capital cost

Low cultivation volume

Patent level, Subitec, Stuttgart, Germany

This is a state-of-art closed PBR design; thus, it requires high capital cost, expertise, and perpetual maintenance. Applicability rating: Low

1. The volume can be up to 200 L
2. It contains four compartments of internal airlift loop reactors using internal baffles
3. Separated into two independent groups using a large internal baffle to prevent complete culture collapse in case of leakage, i.e. two systems of cultivation can run independently
4. The bottom of the reactor is fitted with gas spargers
5. Pump required for aeration should be with $8 \text{ W} \cdot \text{m}^{-3}$

High surface to volume ratio

Low mechanical force on the cells

Low energy consumption

High gas-liquid mass transfer rate

Low operating cost

Long lifespan

Reduced fouling, clumping and cell sedimentation at high liquid velocity

^aPhotoinhibition is when light intensity surpasses the saturation level (the light saturation intensity), the growth of the algae will be inhibited.

^bCAPEX: Capital Expense.

^cOMEX: Operating and Maintenance Expense.

Table 6 | Advantages and disadvantages of different types of flocculation

Type of flocculation	Advantages	Disadvantages
Autoflocculation	Does not contaminate the harvested algae	Slow and unreliable process thereby it is uneconomical
Electroflocculation	Non-species specific, easy to control, low chemical usage, more expected results, no leftover anions (e.g. chloride and sulfate) and low power consumption compared to centrifugation	Requires electrode replacement and maintenance, increase in temperature of algal suspension, changes in pH and leftover metals in the algal concentrate (Vandamme et al. 2011)
Bioflocculation	High efficiency (especially when succeeded by centrifugation), no contamination to the microalgae	Highly species dependent

Gravity sedimentation relies on the characteristic of the suspended solids. Density, radius of algae cells and the induced sedimentation velocity influence the settling characteristic of suspended solids. Microalgae with high density can settle properly, unlike microalgae with low density that do not settle well and are unsuccessfully separated by settling. To accelerate sedimentation, flocculants are usually added. To improve it, lamella separators and sedimentation tanks may be used (Chen et al. 2011). Regarding the household level application, the gravity sedimentation for low density microalgae will not be suitable and would be expensive as lamella separators and sedimentation tanks require huge costs and space and are time-consuming.

Through the usage of electrolysis or pressure relief into the algal suspension, the air bubbles are generated and the microalgae adhere on the bubbles and are separated (Liang et al. 2015). The microalgae are then simply scooped off the surface. This method is effective with low-density microalgae species (Hanotu et al. 2012). This process is combined with flocculation or the addition of surfactants to increase the probability for the air bubble and suspended particle (biomass) to adhere (Gerardo et al. 2015). Flotation efficiency depends on the type of collector (surfactant or

Table 7 | Types of chemical flocculation

Type	Flocculant	Optimal dose (mg/L)	Optimal pH	Comments
Inorganic	Aluminum Sulfate (alum)	342	5.3–5.6	The more electronegative the faster the coagulation The less soluble the salt the more effective
	Ferric chloride	300	6	Large amount of flocculant needed to cause solid-liquid separation of the microalgae Convenient to a few species End-product is contaminated by the flocculants
Organic flocculants (cation, anion, non-ionic)	Dow C31 (cationic polyamine)	1–5	2–4	A small amount is needed The end-product is not contaminated
	Chitosan	10	8.4	Gentle mixing is recommended to speed-up the process
	Magnafloc® LT2	0.25	10.2	
	Dow 21M	10	4.0–7.0	Excessive mixing could disrupt the flocs

Adapted from Liang *et al.* (2015).

flocculants), pH and ionic strength in the medium, type of bubble formation, recycling rate, air tank pressure, hydraulic retention time and particle size (Phoochinda & White 2003). Flotation types are based on their bubble size production. Table 8 summarizes the different types of flotation methods.

In general, the flotation method is usually used for pilot scale as it requires air tanks, chemicals, and experts for operation etc. In other words, it will add more to the capital and operational costs making it inapplicable for household level practice.

Secondary dewatering

The filtration method is based on passing the microalgae culture through filters operating under gravity, vacuum or pressure. The microalgae particles get stuck at the filter, allowing the water to fall through. The size range of micro-algae is typically between 2 and 30 µm. There are different filters based heavily on the microalgae size and, also on the solvent/solute properties, hydrodynamic conditions (Pahl *et al.* 2012). Table 9 summarizes membrane filters based on size.

Table 8 | Summary of different types of flotation methods

Type	Bubble size (micrometer)	Method	Records for operation
Dissolved air flotation (DAF)	10–100 ^a	Bubbles are produced from the pressure relief of water stream that is pre-saturated with air at excess pressures	Using cationic polymer (PolyDADMAC) increases removal efficiency by 95% ^b High energy requirement of 7.6 kWh/m ^{3c}
Dispersed flotation and electrolytic flotation (DiAF)	700–1,500	Formed by continuously passing air through a porous material (diffusers or spargers) or by a high-speed mechanical agitator	Low energy consumption: 0.015 kWh/m ³ when foam fractionation is combined with DiAF ^c High capital cost Collectors such as sodium dodecylsulfate (SDS), chitosan, saponin CTABs etc. have been used to increase efficiency ^{c,d,e} Using 60 mg/L CTAB increases removal efficiency to 83.1% ^e
Electroflotation	32.7–68.6 ^f	Hydrogen bubbles are released from a cathode when connected to an electric field	No chemicals are required, so no contamination Energy efficient Cathodes fouling is likely to happen

^aUduman *et al.* (2010), ^bHenderson *et al.* (2009), ^cWiley *et al.* (2009), ^dKurniawati *et al.* (2014), ^eNguyen *et al.* (2013), ^fAlam *et al.* (2017).

Table 9 | Summary of different sizes of membranes (Singh & Patidar 2018)

Membrane type	Pore size (micrometer)	Notes
Microfilter (MF)	0.1–10	Preferred size, especially for <i>Chlorella</i> sp.
Macrofilter	>10	Usually for larger size cells or flocculated ones
Ultrafilter (UF)	0.02–0.2	High flux requirement High operating and maintenance Not generally used for microalgae Better fouling resistance Selected coagulation pretreatment is preferred

The membrane performance also depends on the construction materials and surface properties, i.e. charge and hydrophobicity (Rossi *et al.* 2004). Accordingly, it was found that positively charged membranes perform worse than neutral ones (Rossi *et al.* 2004). This is because microalgae usually carry a negative charge (Pahl *et al.* 2012) on their surface which would increase its affinity with positive charged membranes leading to fouling of membrane and low permeate fluxes. Moreover, hydrophilic membranes perform better because they have low fouling tendency by extracellular organic matter than hydrophobic membranes (Rossi *et al.* 2004; Sun *et al.* 2013). For hydrophobic surfaces, the fouling formation may be reduced by coating the membrane surface with hydrophilic polyvinyl alcohol polymer. Consequently, the maximum flux can be increased by 36% with surface-coated membranes (Hwang *et al.* 2013). Pretreatment with ozone is recommended as it reduces cake layer formation (a layer formed by organic matter secreted by microalgae) by 70–93% which improves filter performance (Borowitzka & Moheimani 2012). To conclude, negatively charged/neutral hydrophilic membranes are recommended for microalgae filtration because they foul less and have high permeate flux (Sun *et al.* 2013). Table 10 lists the typical membrane materials.

The flow of the culture-to-be-filtered feed is a determinant factor in the efficiency of the filtration method. There is tangential flow filtration (TFF) or dead-end filtration (DEF) using either UF or MF membranes. For tangential flow or cross flow, the flow of diluted algae passes parallel

Table 10 | Typical materials used for membranes (Drexler & Yeh 2014)

Material	Charge	Hydrophobic	Hydrophilic
Polyvinylidene fluoride (PVDF)	Neutral	✓	
Polyacrylonitrile (PAN)	Neutral		✓
Polyethersulfone (PES)	Neutral	✓	
Polytetrafluoroethylene (PTFE)	Neutral	✓	
Polysulfone (PS)	Negative	✓	
Regenerated cellulose acetate membrane (RCA)	Neutral		✓
Polyvinyl chloride (PVC)	Neutral	✓	

to the membrane while the filtrate passes perpendicular through the membrane. It can achieve about 70–80% removal efficiency. For dead end or direct flow, the flow of diluted algae passes perpendicular to the membrane. It is not economical to use due to quick fouling of the membrane. There are vacuum/pressure filtrations which were found to recover a large amount, but they are not suitable to microalgae with dimensions similar to that of bacteria (Molina Grima *et al.* 2003). A major problem with filtration is that it gets clogged up eventually which reduces its efficiency.

Filtration is the easiest and cheapest dewatering method that requires no prior experience to implement at the household scale. Cheap filter membranes, like nylon, are attainable at local markets and can do the job. As for the direction of flow, it is simpler to use direct flow under the force of gravity as it requires no energy input.

Centrifugation is the quickest yet most efficient way of harvesting microalgae. For example, about 80–90% microalgae can be recovered within 2–5 min on pond effluent at 500–1000xg (xg: relative centrifugal force (RCF)) (Molina Grima *et al.* 2003). There are several types of centrifuge that have been examined, including disk stack centrifuges, perforated basket centrifuges, imperforated basket centrifuges, decanters and hydrocyclones (Mo *et al.* 2015). Selection of the appropriate centrifuge is based on its RCF range, the microalgae size it can harvest, effectiveness vs. power consumption, and capital cost. However, exposure of microalgal cells to high gravitational and shear forces can damage cell structure (Chen *et al.* 2011). Also, they

consume a huge amount of energy and they are time-consuming for mass-cultivated microalgae (Singh & Patidar 2018). Pretreatment of the algal with flotation, for example, would reduce the energy consumption by the centrifuge.

Centrifuge is not recommended to be used on a household scale level. It requires energy and the cost is extremely high. Nevertheless, it requires expert or prior-use knowledge to set up the appropriate RCF.

Table 11 is an assessment of the aforementioned harvesting methods adapted from Chen et al. (2011), while it also rates the respective methods' applicability rating from high to low.

In conclusion, the best harvesting method, according to the MENA region, would be filtration as it is cheap, filter membranes are available at local markets, and they do not require energy input or specialized personnel. To make the process more efficient, it can be preceded by flocculation to allow microalgae to be easily filtered.

Drying methods

During the drying process, 90–95% of dry solid is achieved (Borowitzka & Moheimani 2012). There are several methods of drying, as presented in Table 12.

RESOURCE RECOVERY MODEL: MICROALGAE CULTIVATION IN WASTEWATER

Present studies have supported the idea of using microalgae as a novel approach to treat wastewater (WWT). This comes with the fact that microalgae can deal with different types of wastewater constituents, i.e. high nitrogen and phosphorus levels. Microalgae can also be used to treat different types of wastewater sources, i.e. municipal water, livestock effluent, aquaculture, and industrial water. Table 13 displays an overview of the research studies conducted using microalgae to treat different sources of wastewater. One of the widely cultivated species in wastewater is the *Chlorella* sp. (Li et al. 2019). The treated water can be used as irrigation water in agriculture, contributing towards the water scarcity problem. As for the microalgae harvested, it can be used as feed for poultry, it is safe and has shown no toxicity (Abdo et al. 2019). Cultivating microalgae for wastewater treatment,

unlike the conventional activated sludge process, would require longer hydraulic retention times and a vital supply of CO₂ and light. In fact, PBRs designed for WWT take secondary treatment designs in WWT plants as a reference, i.e. PBRs for WWT are classified into two types based on the microalgae cell condition: the suspended system (mobilized microalgae) and the fixed system (immobilized microalgae) (Hoffmann 2002). In the suspended system, the microalgae freely mobilize within the wastewater culture's pollutants. Examples of possible PBR designs would be open pond, tubular PBRs, flat panel PBR, and plastic bag systems. In the fixed system there is a biofilm bioreactor, immobilized bioreactor and microalgae membrane bioreactor (Ting et al. 2017). The separation in suspended systems may be done using coagulation, membrane filtration etc., which in general increases the costs in comparison with conventional methods of WWT. For the fixed system the separation process is improved but there is difficulty in measurement of the biomass (Ting et al. 2017). Suspended systems are more applicable to treat wastewater with high organic loading rates, i.e. effluents from agriculture or livestock. Fixed systems deal well with municipal wastewater as it has a lower organic loading rate, TN and TP. The design of suspended system is determined by the illumination over the PBR while in fixed systems the operation mode and HRT are the factors that conclude its design. Unfortunately, both systems are at lab-scale or pilot scale, and require more research and understanding of the parameters to scale up the system. Table A3 summarizes some of the characteristics of different types of systems, further details about the design may be found in Ting et al. (2017).

Cultivation in wastewater increases susceptibility of infestations. There are many kinds of potential contaminants in algal ponds. There are predators such as amoebae, ciliates, other predatory algae (that feed on cyanobacteria), rotifers, flagellates, and crustaceans (Carney & Lane 2014). There are pathogens like viruses, bacteria, and fungi that can infect the culture. Finally, there are competitors, like other microalgae that can outcompete the microalgae that was intended to be grown. These kinds of contaminations, when they take place, cause complete loss of the biomass. In fact, production ponds are estimated to be non-productive 12–30% of a growth season due to contamination incidents. In addition, recovery from such

Table 11 | Summary of harvesting methods (Chen et al. 2011)

Method	Energy demand	Achievable solid concentration	Advantages	Disadvantages	Household Applicability rating
Flocculation	Low 1.3 kWh/m ³ of medium, depending on plant size	1.5–5%	<ul style="list-style-type: none"> - Suitable for large scale application - Less cell damages - Applied to vast range of species - Less energy requirements 	<ul style="list-style-type: none"> - Metal contamination (by inorganic flocculants) - Chemicals may be expensive - Highly pH dependent - Difficult to separate the coagulant from harvested biomass - Culture medium recycling is limited 	High (for autoflocculation) Medium (for electroflocculation) Low (for bio/chemicalflocculation)
Flotation	Low	4–8%	<ul style="list-style-type: none"> - Short operation time - Low space requirement - Large scale harvesting - Low initial cost (surfactants are required) - Suitable for large scale application 	<ul style="list-style-type: none"> - Needs surfactants - Presence of contaminants on final products 	Low
Filtration	Low Primary step – 0.32 kWh/m ³ Secondary step – 1 kWh/m ^{3a}	Primary harvester – Approx 3% of total suspended solids (TSS) Secondary dewatering – 15–25% TSS	<ul style="list-style-type: none"> - High recovery efficiency - Cost effective - No chemical required - Low shear stress - Water recycles - No contamination 	<ul style="list-style-type: none"> - Slow, requires pressure or vacuum, which would consume high energy - Not suitable for small algae - Membrane fouling/ clogging take place and replacement increases - Operational and maintenance costs 	High
Centrifugation	Very high 0.85–0.95 kWh/m ³	15–30%	<ul style="list-style-type: none"> - Fast and effective technique - High recovery efficiency (>90) 	<ul style="list-style-type: none"> - Expensive technique with high energy requirement - High operation and maintenance costs - Time consuming and too expensive for large scale - Risk of cell destruction - AOM^a and EOM^b released - cause toxicity 	Low

^aAlgae Organic Matter, ^bExtracellular Organic Matter.

Table 12 | Summary of drying methods options (Chen et al. 2015)

Method	Description	End-product usage	Advantages	Disadvantages	Household Applicability
Solar drying	Drying by direct sunlight or circulating airflow. The algae may also be placed under transparent glass or sheet which raises temperature, speeding up drying. Overheating can be lowered using a solar water heating system.	Biodiesel production	Cheap and economical Accessible at most areas Fast drying when high temperature (<10% moisture is achieved in 3–5 h at 60 °C)	Slow drying rate at low temperatures which may induce cell decomposition due to bacterial contamination Unreliable source, only visible during the day Uncontrollable, high and low temperature vary Requires large space to spread the algae	Easiest and free of charge method, although dependent on the region's weather and solar radiation rates but is economical. It requires large area but for household scale (can be dried on rooftops) and the area is not an issue since the yield is not equivalent to industrial production. It is time consuming Applicability rating: High
Spray dryers	Drying is carried out by hot steam which is sprayed downward on the algae. It turns the algae into powder form.	Food production Pigments extraction	Very efficient drying method Large number of algae constituents is preserved The residual moisture in the product is 4%	Intact cells may rupture due to its high-pressure atomization process High operating cost	They are expensive, high operational costs and usually used for R&D purpose, so they require expertise. Thus, they are not recommended for household usage. Applicability rating: Low
Freeze drying	Work by freezing the material, then reducing the pressure and adding heat to allow the frozen water in the material to sublimate.	Food production Pigments extraction	All the cell constituents are preserved without rupturing the cell wall	Only employed in lab-scale High energy consumption	Similar to spray dryers. So, they are not recommended for household usage Applicability rating: Low
Drum drying	The use of a sloped rotating cylinder onto which the material being dried (using hot stream of air or gas) is conveyed from one end to the other by gravity and built-in baffles.	Food production	Simultaneous sterilization and cell decomposition	High energy cost	They require high operational and energy costs. They are used for larger scale production so, they are not recommended for household usage Applicability rating: Low

Table 13 | Nutrient profiles of wastewaters applied for algae cultivation and the nutrient removal rates

Wastewater source	Wastewater characteristics				Removal rate (%)				Ref.
	COD (mg/L)	TN (mg/L)	TP (mg/L)	Microalgae species	COD	TN	TP		
Municipal wastewater	103–190.9	23.1–35.4 ^a	3.8–4.9	Filamentous blue-green algae	98	76.6–97.8 ^a	54.5–72.6	Su et al. (2011)	
	178.4	39.5	5.3	<i>Coelastrum microponum</i>	59.5–80.3	35.2–87.8	43.4–88.7	Lee et al. (2015)	
	2,304.0–2,389.5	116.1–132.3	212.0–215.1	<i>Chlorella</i> sp.	90.8	89.1	80.9	Li et al. (2011) ^b	
Agricultural wastewater	700–1,280	109–239 ^a	15.3–29.5	<i>Chlorella</i> sp.	27.9–38.4	75.7–82.5	62.5–74.7	Wang et al. (2010)	
Industrial wastewater	2,100–3,020	197.6–251.0	16.3–29.7	<i>Chlorella</i> sp.	7.95–43.91	30.06–50.94	44.95–63.51	Lu et al. (2015)	
	5,000	600 ^c	75 ^c	<i>Scenedesmus</i> sp.	87.2	90.2	88.6	Ma et al. (2017)	

^aThe value is TKN here.

^bThe centrate, which is the liquid from activated sludge thickening process belonging to the municipal wastewater, was used.

^cThe TN and TP were increased from 458 and 67 to 600 and 75 mg/L, respectively, to suffice the nutrient requirement for cell growth.

***Note. Adapted from Li et al. (2019).

accidents is slow, expensive, and labor intensive. One of the common methods to mitigate contaminations is to deploy an integrated pest management plan (Carney & Lane 2014). This plan consists of a method to identify pests/predators, developing tracking devices to monitor the population of pests and finally creating intervention responses. Intervention and control systems include salvage harvest, using chemicals such as abscisic acid, fungicides, altering growth conditions such as pH controls and ammonia exposures (McBride et al. 2014; Ganuza et al. 2016). Physical methods include sonication and filtration. Finally, there are biological methods such as introducing predators to parasites. For example, zooplankton can be used to prey on fungal spores (Kagami et al. 2004).

POTENTIAL OF HOUSEHOLD PHOTOBIOREACTOR (H-PBR)

Climate change is the biggest challenge the globe is facing right now. It is the trigger that is pushing other disasters to take over, such as famine, water scarcity, health problems, etc. Earlier, the threat posed by climate change to the agricultural sector was discussed. People living in developing countries, specifically the inhabitants of rural areas, are the most vulnerable to such threats. Aside to malnutrition issues, their standards of living are perpetually jeopardized by an unhealthy surrounding environment. Climate change also impacts their health. The air they breathe is usually contaminated by nearby factories, especially elevated CO₂ levels in the air, which is a worldwide problem as well. Studies have shown that high CO₂ concentrations causes health problems, even if it is for a few hours (Jacobson et al. 2019). So, poorly ventilated classrooms, office environments, and bedrooms, where people spend most of their days inside, are areas where CO₂ concentrations are between 600 and 1,000 ppm and could exceed 2,000 ppm (Colton et al. 2014; Fisk 2017; Persily & de Jonge 2017). Health problems at such concentrations lead to inflammation, bone demineralization, behavioral and physiological changes, and oxidative stress (Jacobson et al. 2019). Consequently, this could impede regular daily activities making them less active and affecting their employment. Alongside climate change, most rural areas are not connected to a wastewater

grid. The waste produced by the locals and their livestock is stored in septic tanks which are emptied on a weekly basis, if ever. These septic tanks are a hub of diseases that could affect vulnerable people such as children. Moreover, for farmers, there is a struggle to find affordable fertilizers and feed for the cattle. All in all, there is a desperate need for action, whether by the government or individuals, to mitigate such threats.

After investigating these problems, we present the idea of a household photobioreactor as a potential solution. As mentioned previously, the potential of microalgae is vast. It can help reduce CO₂ in indoor environments more than common indoor plants. It provides a means of water management as it can grow in wastewater while detoxicating it which can then be used for irrigating the plants/crops. This could also encourage the farmers to plant trees around their homes, which could protect their homes from severe winds and cold days. Microalgae is also undeniably a nutritional source of feed, however, if cultivated in wastewater it would be safe to use simply as a soil conditioner or feed for poultry (Abdo et al. 2019).

There are several easy configurations that are suitable for H-PBR, as shown clearly in Tables 4 and 5. In the following paragraphs, two H-PBR configuration scenarios will be discussed. One scenario is based on the availability of a backyard for a customer which means there is an adequate surface area and the other scenario assumes that the customer has no backyard which means perhaps this is a building, apartment, office, or rural area. For the first scenario, the raceway pond configuration would be most applicable. A raceway pond outline can be constructed by cementing bricks to one another and creating an inner outline of polyethylene (or any unreacted material) while separating the two lanes using plexiglass. Other technical inputs would be proper lighting (sunlight is sufficient) and a paddle. The volume of the pond should vary between 500 and 1,000 L to harvest a profitable quantity of microalgae. For example, according to Piccolo (2011), 1 m² of water will produce 10 g of *spirulina*, so to produce 1,000 g, 100 m² of pond is needed, i.e. 5 m wide and 20 m long. However, such size is not applicable at the household scale. In the second scenario, a bubble column or plastic PBR would be applicable, taking a column reactor as an example. The outline of the column reactor can be obtained from any local

market, and the material can be plexiglass. To satisfy the geometric relation mentioned in Table 5 for the column PBR design parameter while also suitably sized for an indoor H-PBR, the diameter of the column can range from 0.1 to 0.25 m while the height can be from 0.3 to 0.5 m. Based on these specs, the volume can range from 9.5 to 100 L. Bubble column reactors require air spargers attached to an air pump and an LED lamp if placed indoors in case of little or no available sunlight.

For both scenarios the inoculum must be obtained from local labs initially. Later, the owner must not harvest the microalgae entirely. The media (wastewater) must be first evaluated by local laboratories to see if all nutrients are available at sufficient concentrations, and if not, the nutrients can be supplied readily by the manufacturer. The harvesting is based on Tables 11 and 12, using simple auto-flocculation followed by filtration then solar drying. To conclude, the procedure itself is not complicated and does not require expertise, given it is only for household scale.

Finally, H-PBR should not be a solution solely for farmers, as urban citizens can also benefit from growing microalgae indoors. They can act as mere decorations while purifying indoor air quality and be harvested as supplements. The idea of this is to encourage people to realize the immense potential of microalgae. In fact, in 1974, microalgae was declared as 'the best food for the future' by the United Nations World Food Conference. Moreover, in 1993 during the United Nations World Health Organization (WHO), it was stated that 'We at WHO consider it [Spirulina] a very suitable food.' It is unfortunate that the idea of ingesting microalgae is repulsive. Hence, through the utilization of H-PBR, humans shall understand the potential health benefits microalgae can induce and their impact on the environment. Indeed, H-PBR can be a step forward towards sustainable living, a goal that is preached by global organizations.

Business model of household photobioreactor

With all the vast benefits and untapped potential, a business venture must be established to connect the people to these benefits. As a matter of fact, a business venture in this field would be profitable, whether it is for the direct user of H-PBR or the manufacturer of an H-PBR system. Thus,

the aim of this section is to discuss the business scenario and provide a financial breakdown for the H-PBR business owner and the H-PBR supplier, which could be a source of jobs for dozens of individuals. According to the previous section it can be concluded that the basic technical inputs needed are: raceway pond/column PBR, paddle/air sparger and motor, harvesting tools, dryer tools, culture and nutrients. To get in contact with contractors to provide the materials for all of this is tiresome. Therefore, it is recommended that H-PBR manufacture and a market moderator must be founded as a business which would provide all the technical equipment. In brief, the H-PBR manufacturer shall be in connection with contractors, lab technicians, and market merchants. An individual interested in purchasing the H-PBR (farm manager, family member) must contact the H-PBR manufacturer for technicalities, payment plans, and H-PBR designs. The individual can also return to the H-PBR manufacturer with his harvest to sell it at a profit. In conclusion, the farm manager would

only manage the process of cultivating and harvesting the microalgae, so the business side is left to the H-PBR manufacturer. Table 14 summarizes a financial breakdown for both H-PBR scenarios. Costs provided in the table are based on Egyptian market surveying. Hence, it is worth noting that these prices could be lower or higher depending on the region. Accordingly, the capital and operational costs would be approximately US \$600 and US \$50 for raceway H-PBR, respectively, while for the column H-PBR it would be US \$200 and US \$40, respectively. Based on the aforementioned H-PBR specs in the table, the daily average production rate raceway pond and column H-PBR would be 45 and 10 g, respectively. Based on the Egyptian market, 1 g of spirulina dried powder is equivalent to US 1.25 EGP (US \$0.08), hence, an annual net profit (given the farm produces on 5 days weekly, calculated using Equations (3) and (4) then converted to an annual basis) for the farm manager of the raceway pond and column H-PBR of approximately US \$770 and US

Table 14 | Financial breakdown of H-PBR

Capital Cost

H-PBR Type	Raceway	Column	Cost (EGP)
4.5 m ² raceway pond structure (1.5 m W × 3 m L × 0.2 m H) HDPE plastic	<input type="checkbox"/>		1,500.00
Column shaped transparent plexiglass material (0.25 m D, 0.5 m H)		<input type="checkbox"/>	1,000.00
LED lamp		<input type="checkbox"/>	100.00
UV. Proof covers	<input type="checkbox"/>		1,500.00
350 W washdown gear motor	<input type="checkbox"/>		4,000.00
Paddle wheel and fittings	<input type="checkbox"/>		1,000.00
Air Sprarger		<input type="checkbox"/>	950.00
Filter Mesh - Nylon (1 m ²)	<input type="checkbox"/>	<input type="checkbox"/>	400.00
Culture cost	<input type="checkbox"/>	<input type="checkbox"/>	500.00
Total Capital Cost	EGP 8,900.00	EGP 2,950.00	

Monthly operational costs

H-PBR Type	Raceway	Column	Cost (EGP)
Nutrients	<input type="checkbox"/>	<input type="checkbox"/>	100–500.00
Labourers (recommended)	<input type="checkbox"/>		80.00
Maintenance 10% of piping costs	<input type="checkbox"/>	<input type="checkbox"/>	100.00
Total Operational Cost	EGP 680.00	EGP 200.00	

\$140 respectively.

$$\begin{aligned} \text{Monthly Gross Profit} &= \text{Average daily production of algae (g)} \\ &\times \frac{\text{Price of microalgae}}{1 \text{ g of algae}} \\ &\times \text{No. of days of production} \end{aligned} \quad (3)$$

$$\begin{aligned} \text{Monthly Net Profit} \\ = \text{Monthly Gross Profit} - \text{Monthly Operational Costs} \end{aligned} \quad (4)$$

Therefore, the return period, calculated using Equation (5), for the raceway pond would be approximately nine months while the column would be almost 1.4 years.

$$\text{Payback Period (years)} = \frac{\text{Capital Cost (Initial Investment)}}{\text{Annual Cash Inflow}} \quad (5)$$

Finally, in order to approximate prices when scaling up items, it is preferred to use Equation (6) below:

$$\text{CostB} = \text{CostA} \left(\frac{\text{SizeB}}{\text{SizeA}} \right)^n \quad (6)$$

The exponent value n is specific to the type and quality of the equipment, but it can be assumed as 0.85. However, Equation (4) is not applicable when the ratio between the sizes is greater than 10 (Ación et al. 2017). For such inconvenience, it is advisable to use multiple units of the same equipment. In conclusion, when investing into an H-PBR is not only about creating a profitable revenue stream but it is mainly about integrating a sustainable lifestyle in day-to-day lives. Table 15 demonstrates the business model of the H-PBR manufacturer.

Challenges and opportunities










The opportunities presented in this paper for microalgae cultivation prove that they are sustainable, climate-friendly, environmental and a feasible proposal at a household level. They are also deemed as an appropriate technology, i.e. it is a technology that is not technically complicated yet is sophisticated through its simplicity that tackles a detrimental local

problem by finding a solution which would be environmentally safe, fulfil human needs and help the local economy to flourish. In developing countries climate change impacts are increasing dramatically, and food insecurity is a focal issue. While governments may be drafting long term solutions, the resources allocation would still be prioritized in mega projects rather than decentralized approaches. Indeed, permanent solutions need to be created to sustainably develop decentralized communities. Household scale is an investment opportunity. Its implementation would not only resolve the environmental issues but also contribute towards the general health of the public. Despite the simplicity in understanding the cultivation of microalgae, the technology, economic viability, and relevant socio-cultural factors impede the microalgae cultivation from being easily executed in practice. This section presents the palpable challenges of microalgae cultivation, especially when scaling-up for household level.

Technical challenges

The technological aspect in the microalgae cultivation is not entirely fulfilled from the research base for household scale (Xu et al. 2019). Indeed, this scale has limited research in terms of design bases for flow and mass transfer. In addition, there are insufficient studies that can fully monitor and predict the growth of microalgae which could give insights into the amount expected to be harvested. Thus, household PBRs encounter a challenge in capturing light properly, the volume to surface ratio ought to be improved further. Further research and studies are needed to optimize the design of the PBRs while reshaping the cost-structure to make it economically feasible and simple to construct. Current industrial-scale productions dealing with major bottlenecks are associated with downstream processes. The density of microalgae cells is similar to that of water, making the harvesting process inefficient and time-consuming. For household scale, this may not be a major issue since the amount harvested is not huge and local materials can be used as harvesting tools. However, as for household scale, technical problems include media costs and cultural instability. Media costs (water, nutrients, trace elements) could be compensated in case the desired end product is a soil fertilizer or feeder for cattle and fish using domestic and agricultural wastewater as the source of

Table 15 | Business model for household bioreactor manufacturer

 Key Partners	 Key activities	 Value propositions	 Customer relationships	Customer segments 
<ul style="list-style-type: none"> ✓ Women in households ✓ Private sector ✓ Development Partner ✓ Authorities that connect the locals to the government ✓ Lab specialists 	<ul style="list-style-type: none"> ✓ Design bioreactors ✓ Create contract and forms ✓ Design simple monitoring systems for growth ✓ Manufacture the bioreactor through contractors ✓ Recourses recovery ✓ Value added products (bioproducts) 	<ul style="list-style-type: none"> ✓ Bioproducts ✓ Resource recovery ✓ Wastewater management ✓ Mitigate air population ✓ Improves public health ✓ Create jobs 	<ul style="list-style-type: none"> ✓ Raising awareness, capacity building ✓ Contract based and forms ✓ Technical support ✓ Monitoring progress ✓ Market support 	<ul style="list-style-type: none"> ✓ Households ✓ Farmers ✓ Private sector
	<ul style="list-style-type: none">  Key Resources ✓ Photobioreactor ✓ Qualified laborers 		<ul style="list-style-type: none">  Channels ✓ Door-to-door ✓ Word of mouth between locals ✓ Workshops by NGOs ✓ Distributed brochures 	
<ul style="list-style-type: none">  Cost Structure ✓ CAPEX – materials to construct the unit, materials to harvest the algae ✓ OPEX – the harvesting tools and maintenance of the unit ✓ Management express ✓ Transportations 			<ul style="list-style-type: none">  Revenue Streams ✓ Selling ready installed household level PBR units ✓ Selling the algae in case of large scale 	

nutrients, while for producing high quality species that can be used to boost individual immune systems and productivity, media with high purity is required and in this case wastewater could not be used. In both cases, the carbon dioxide level in the surrounding environment will be absorbed in the photosynthesis of microalgae cultivation.

Financial constraints

As mentioned previously, due to the low efficiency and high energy required, about 50–60% of the microalgae cultivation process goes to the downstream process. It is both high in energy and requires a vast amount of cost, especially for the industrial scale. Developing economically efficient methods is needed for financial stability. Technologically, there is still ongoing research into developing inexpensive yet fast methods. Business-wise, designing centralized downstream processing and using solar energy for drying processes that could serve two or more industrial plants could overcome the economic challenges of using PBR. However, a cutting-edge solution would be one that could

make use of the microalgae without the need to go through the entire down-stream processing, i.e. utilize the microalgae in its slurry phase. In addition, microalgae cultivation requires several resources (water, land, nutrients, energy, etc.). Some of these resources could be compensated. For example, using wastewater as cultivation media would compensate for the water and nutrient costs. Using wastewater requires perpetual maintenance and monitoring to ensure the microalgae are not outcompeted. Such activities involve costs as well.

Social acceptance

The use of microalgae is not exclusive to the 21st century. In fact, microalgae were used as a source of therapeutic medicine thousands of years ago by the indigenous population in China, the Mayan civilization, and some communities in Africa such as Niger and Chad. However, there are still several social challenges around acceptance of the utilization of microalgae, especially as a source of vitamins in developing countries, and this is perhaps due

to a lack of awareness. There is still a huge gap in the market for microalgae. Recently, research has showcased microalgae integrated with flour to create edible spaghetti to prove its increased nutritional value (Fradique *et al.* 2010). Moreover, the declaration made by the UN that it is the 'the best food for the future' and recommendations made by WHO would surely encourage people to include it into their diet. However, beyond the mindset issue with microalgae, there is a lack of learning culture and constructive criticism and contractors look for traditional and safe ways to secure their business and do not seek innovative methods. There is also a lack of skilled personnel in Egypt in rural areas. Consequently, there is a need for raising awareness about the potential of microalgae, training on the use of household scale bioreactors, and monthly follow-ups to ensure smooth operation of the cultivation process.

Way forward

Theoretically, the potential of the household scale is feasible to achieve and the business model behind it is promising. The idea is to fulfill this both from a social and economic aspect. However, practically, there is still more empirical-based information needed to learn about the definite specs, costs, challenges and so on. To do this, first, screening for technical feasibility, materials, and microalgae species that are available locally should be carried out. The screening would allow for the designer to identify the challenges and limits of the household scale. Conventional microalgae species that have been cultivated locally must be known and based on that, the growth conditions and nutrients required must be identified. Then, an empirical study must be carried out to determine the optimum specs (volume-to-surface ratio) and mixing rate for an improved biomass productivity rate and gas exchange. There must also be a full investigation into the prime methodology for harvesting and drying microalgae, as there are a series of methods that are integrated. For example, chemical flocculation followed by filtration is a speedy and economical method for harvesting followed by solar drying. Based on the previous data, an economic feasibility study must be performed in order to accurately conclude whether the household scale would be applicable for a particular community, taking into account

the social status and environmental conditions (urban or rural area) of the customer.

CONCLUSIONS

There are undeniably environmental crises taking place around the world that challenge current practices in the industry and call for change. Untapped potential through biotechnology can be a solution to several environmental issues. One competitive biotechnology approach is the PBR for microalgae cultivation that is able to mitigate the climate change impacts and fulfill food security needs. Several countries around the world have considered the implementation of large scale PBRs for microalgae cultivation but it requires a huge investment into advanced cultivation and downstream processing. Therefore, scaling-down the industrial PBR to household level could be a global emerging solution to cope with environmental and economic challenges, to tackle the rising environmental concerns and cope with economic challenges. This paper is designed to be a comprehensive source for technical aspects related to microalgae cultivation and proposes household PBR potential and a business model that would have significant economic, social and environmental implications. Economically, microalgae produce bioactive compounds which are a rich source of nutritional feed for humans and can be also be fed to fish and cattle. Socially, the process of understanding the concept of microalgae cultivation is a means of educating unprivileged individuals, providing them with environmentally related insights and handcraft skills. Environmentally, the photosynthesis process of microalgae will absorb CO₂ and provide a healthier environment. Although there are several challenges with regard to decentralized PBR technology, the potential of this tailor-made approach will enrich the circular economy, enhance environmental conditions, and create a new affordable channel for developing communities to cope with climate change implications.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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