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Strategies to Produce Cost-Effective Third-Generation Biofuel From Microalgae

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Third-generation biofuel produced from microalgae is a viable solution to global energy insecurity and climate change. Despite an annual current global algal biomass production of 38 million litres, commercialization confronts significant economic challenges. However, cost minimization strategies, particularly for microalgae cultivation, have largely been excluded from recent studies. Therefore, this review provides essential insights into the technologies and economics of cost minimization strategies for large-scale applications. Cultivation of microalgae through aquafarming, in wastewater, or for biogas upgrading, and co-production of value-added products (VAPs) such as photo-bioreactors, protein, astaxanthin, and exopolysaccharides can drastically reduce biodiesel production costs. For instance, the co-production of photo-bioreactors and astaxanthin can reduce the cost of biodiesel production from \$3.90 to \$0.54 per litre. Though many technical challenges need to be addressed, the economic analysis reveals that incorporating such cost-effective strategies can make the biorefinery concept feasible and profitable. The cost of producing microalgal biodiesel can be lowered to \$0.73kg^{-1} dry weight when cultivated in wastewater or \$0.54L^{-1} when co-produced with VAPs. Most importantly, access to co-product markets with higher VAPs needs to be encouraged as the global market for microalgae-based VAPs is estimated to rise to \$53.43 billion in 2026. Therefore, policies that incentivize research and development, as well as the production and consumption of microalgae-based biodiesel, are important to reduce the large gap in production cost that persists between biodiesel and petroleum diesel.

Keywords: microalgae, biodiesel production, value-added products, biogas upgrading, wastewater, economic analysis

INTRODUCTION

Rapidly progressing industrialization coupled with the expanding world population is driving energy to become more and more important for economic growth (Ahmed et al., 2021a). The overreliance on fossil fuels poses a threat not only to world energy security, with the current source dwindling and expected to last less than 80 years (Baicha et al., 2016), but is also causing global climate change, ecological degradation, and health issues among humans (Yin et al., 2020). As the fourth largest

TABLE 1 | Advantages and disadvantages of microalgae-based biofuel (Vassilev and Vassileva, 2016).

Advantages	Challenges
Sustainable, renewable and environment friendly	Need to use fossil fuel-based sources during cultivation
Nonedible and non-toxic resources	High production costs for growing, harvesting, collection and transportation
High energy conversion efficiency by photosynthesis	Pretreatment is needed to process the biomass for biofuel production
High productivity, rapid growth rate and high growing yield	Low lipid extraction efficiency
Easily adaptable in a wide range of climatic conditions	High initial capital investment
Easy to culture and fast bioengineered	High biofuel production cost
Abundant and relatively cheap resource	Nutrient-rich water or fertilisers are needed for the cultivation
Can grow in arable land	Commercialisation is not easy
Biodegradable resource with fast bioremediation	

energy source after fossil-based sources, biomass and combustible renewable sources (Lam et al., 2019; Hoang et al., 2021) are promising alternatives with the capacity to address global energy needs (Azevedo et al., 2019). Biodiesels (Mofijur et al., 2020), which are mixtures of fatty acid methyl esters formed through transesterification processes of biomass sources (Hazrat et al., 2021), compose more than 80% of total biofuel production (Yin et al., 2020). The first and second generations of biodiesels, derived from edible food crops and agriculture or lumber waste respectively, have not been well-received due to the resulting stresses on land use and food security, as well as costs related to the feedstocks (Tshizanga et al., 2017).

Third-generation biodiesel from microalgae represents a viable option with its capacity to rapidly accumulate lipid and opportunities for year-round harvesting cycles, the ability of microalgae to double their biomass weight quickly, and microalgae's ease in utilizing sunlight, water, and CO_2 (Mubarak et al., 2019; Yin et al., 2020). **Table 1** shows the advantages and disadvantages of microalgae-based fuel. Currently, an global algal biomass production stands at 38 million litres (Karthikeyan et al., 2020). However, the commercialization of biodiesel production from microalgae faces serious bottlenecks in terms of economic feasibility and life cycle assessment (Chen Jiaxin et al., 2018). For one, due to high costs, microalgae biodiesel production is still primarily limited to the laboratory and pilot scale (Mathimani and Mallick, 2018). Despite this, several strategies have been developed to lower the cost of microalgal biodiesel production, discussions of which have been largely excluded from the recent literature that primarily focuses on the benefits and composition of microalgal biodiesel, insights into the processes and process factors that affect yield, and efficient harvesting and extraction methods (Satpati and Pal, 2018; Shin et al., 2018; Tan et al., 2018; Deshmukh et al., 2019; Goh et al., 2019; Peng et al., 2020; Ananthi et al., 2021). Moreover, cost minimization strategies have been applied primarily to dewatering, harvesting, and pretreatment mechanisms to minimize the total production cost (Kang et al., 2018), rather than cultivation which can also make up a significant proportion of the cost. In addressing these knowledge gaps, this review paper briefly provides some essential insights into the technologies and economics of techniques used to reduce costs for microalgae-based biodiesel production to guide future research into large-scale applications.

Cost-Effective Strategies for Microalgae-Based Biofuel Production

Cultivation of Microalgae in Aquaculture Water

Using microalgae in aquaculture has been recently gaining traction in terms of industrial application due to several advantages (Han et al., 2019). For instance, microalgal cells can filter dissolved wastes that have the potential to initiate eutrophication which would otherwise hamper fish breeding and growth. They also serve as active bio pumps that fix CO_2 levels and provide continuous oxygen to fish (Lu et al., 2019). Additionally, marine microalgae are known to promote fish growth because they supply antioxidants that can improve fish immunity and reduce morbidity, thereby preventing antibiotic abuse (Li et al., 2021).

The lipid-derived from microalgae used in animal feed can assist in resolving digestibility concerns and increasing protein access to cell walls. However, microalgae serve as a fish feed with high levels of protein, lipid, and carbohydrate, adding value-added feed for fish rearing (Lu et al., 2019). Therefore, some microalgae secrete toxic compounds that can affect aquatic health. Regardless, a proper cost evaluation investigating microalgal-based biodiesel production with simultaneous aquafarming is yet to be done, so the implications are currently ambiguous.

Production of Microalgae Oil With Other Value-Added Products

In addition to biodiesel, microalgal cells can also synthesize value-added products (VAPs) like vitamins, terpenoid, flavonoids, pigments, alginate, agar, protein, polyunsaturated fatty acids, polysaccharides, polyhydroxy butyrate (PHB), astaxanthin, anti-oxidants, phytosterols, and hormones (Yang et al., 2019; Aslam et al., 2020; Desjardins et al., 2020; Levasseur et al., 2020). VAPs (Ge et al., 2021) produced from microalgae have extensive applications in the health sector by contributing anti-cancerous, anti-inflammatory, anti-microbial, anti-coagulating, and cholesterol-lowering agents, as well as in pharmaceutical and personal care products (Kothari et al., 2017). Many VAPs are already being manufactured as commodities in different industrial and commercial sectors.

Often, the residual microalgal cell matters are dumped as waste, as illustrated in previous economic analysis, making the processes less cost-effective (Hanifzadeh et al., 2018). Co-producing VAPs with biodiesel (Azad et al., 2018) from microalgae can significantly lower the costs of microalgae biorefineries. In fact, post lipid extraction, an abundant amount of carbohydrates still remain in the cell debris that can be processed into products, e.g., biogas and ethanol (Zhang et al., 2018), further adding to the energy generation potential of microalgal products. Moreover, even though less extensively studied, microalgae also serve as a great food source including for humans, where the microalgae products of *Chlorella* (green algae) and *Spirulina* (cyanobacterial) are effectively used at an industrial scale (Aslam et al., 2020). Nevertheless, there is still a crucial need for the evaluation of the quality of the VAPs co-produced with biodiesel after extraction to assess the techno-economic feasibility of the specific processes.

Utilization of Microalgae Oil for Biogas Upgrading and Simultaneously Producing Oil

As the importance of CO_2 emission mitigation is becoming recognized, the biogas market is predicted to expand, with applications ranging from cooking, heating, power generation, and transport (Siddiki et al., 2021a). Biogas is treated in two steps before utilization: firstly, the harmful and toxic compounds are removed, and secondly, it is upgraded by adjusting the CO_2 content to establish a high calorific value (Awe et al., 2017). However, these upgrading technologies are not feasible in large scale applications (Qyyum et al., 2020).

Autotrophic microalgae can be used to capture CO_2 and convert them into lipids to improve the methane (CH_4) content of biogas. The purchase and supply of additional CO_2 to enhance biomass levels is one of the key reasons for the high production cost of biodiesel (Chang et al., 2018). Even though several studies investigating microalgae, such as *Leptolyngbya* spp., *Chlorella* spp., *Scenedesmus* spp., *Anabaena* spp., *Nannochloropsis* sp., and *Selenastrum* spp., have reported a CO_2 removal efficiency of >90% and an increase in the CH_4 concentration in biogas of up to more than 90%, only a small number of oleaginous microalgae were researched for their capability to collect lipid in a biogas upgrading system (Srinuanpan et al., 2020). Tongprawhan et al. (2014) found that after optimization, the marine *Chlorella* sp. removed 89.3% of CO_2 and improved the CH_4 concentration by up to 94.7%, with lipid productivity of 94.7 $mgL^{-1}day^{-1}$.

Several other studies (Srinuanpan et al., 2019, 2018, 2017) found that *Scenedesmus* sp. can increase the CH_4 concentration in biogas to greater than 90% and improve the final biomass and lipid productivity by 1.25 and 1.79 fold, respectively (Srinuanpan et al., 2017). The processes were also reported to generate microalgal biomass of above 2.98–4.40 gL^{-1} with a lipid content of greater than 34% and consisting of long-chain fatty acids (Srinuanpan et al., 2019, 2018). Similarly, Khan et al. (2018) found a CH_4 content improvement of 81.6%, with a high-quality lipid accumulation of 26% based on microalgal dry mass. In particular, microalgal co-cultivation with bacteria or fungi has A proven greater energy and CO_2 removal efficiency (Zhang et al., 2020). Therefore, anaerobic digestion integrated autotrophic microalgal cultivation represents an ideal "waste biorefinery" (Uddin et al., 2021). Nevertheless, challenges related to the optimization of process parameters and the selection of a robust microalgal strain that can tolerate extreme pH levels, accumulate large amounts of lipid, and utilize organic and inorganic compounds pose major challenges for this process integration (Chen Y.di et al., 2018).

Cultivation of Microalgae for Wastewater Treatment and Simultaneous Lipid Extraction

Numerous studies have revealed the potential for oleaginous microalgal cultivation in wastewater for producing biodiesel, where microalgae have exhibited significant efficiency in removing the contaminants from wastewater (Ahmed et al., 2021b) and the capacity to collect lipid in the cell body. Microalgae can be cultivated in both municipal wastewater and industrial effluents (Ahmed et al., 2021), for example, from rubber and palm oil mills and the textile industry, and in starch wastewater and wastewater containing heavy metals (Mohd Udaiyappan et al., 2017; Shen et al., 2017; Srinuanpan et al., 2020). For instance, *Choleralla* sp. was found to remove 75% of the chemical oxygen demand (COD) of textile wastewater while accumulating 20% lipid in cell dry weight (Wu et al., 2017). The cultivation of *Botryococcus braunii* in wastewater removed 100 and 65% of total phosphorous and total nitrogen, respectively (Rinna et al., 2017). Similarly, another study that used *Botryococcus* sp. to treat domestic effluent found that the microalgae were able to remove 64.5, 89.8, and 67.9% of total nitrogen, total phosphorous, and total organic carbon, respectively, and was also able to accumulate up to 61.7% w/w dry cell lipid (Shen et al., 2017).

Many studies (Malibari et al., 2018; Enwereuzoh et al., 2020, 2021) have also revealed that the nutrients in fish farm effluents are suitable for algal biomass cultivation suitable for producing biodiesel, where *Chlamydomonas reinhardtii* has the most suitable properties for biodiesel production. Moreover, the removal of endocrine disruptors, a group of alarming, emerging contaminants of the contemporary world that can have adverse impacts on human health (Ahmed et al., 2021), can also be achieved through microalgae cultivation (Hena et al., 2020). Several investigations have explored the potential of integrating several different processes, such as biogas upgrading and wastewater treatment with microalgae. For instance, growing *Chlorella* spp. in municipal effluent not only upgraded the biogas to a more than 90% CH_4 content, but was also successful in eradicating more than 80% of the COD, and more than 70% of the total nitrogen and total phosphorous from the wastewater (Srinuanpan et al., 2020). When cultivated in swine wastewater, *Scenedesmus* spp. was also found to upgrade the CH_4 content of the biogas to above 70% while displaying a removal efficiency of above 60% for COD, total nitrogen, and total phosphorous (Cheirsilp et al., 2017; Srinuanpan et al., 2020).

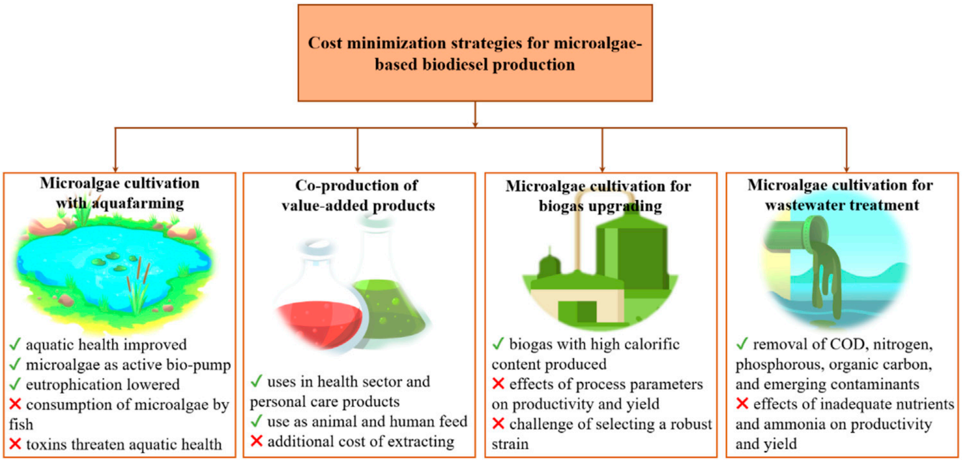

FIGURE 1 | Cost minimization strategies for large-scale microalgae-based biodiesel production.

Microalgal cultivation in food industry effluents incorporating high VAP generating routes can also prove to be a promising option to undertake waste source reduction, conversion, and re-utilization on a commercial scale (Li et al., 2019). Nevertheless, insights into the simultaneous production of biodiesel with integrated processes are largely absent. Biodiesel production combining microalgal bioremediation of wastewater can effectively lower process costs due to the simultaneous achievement of both energy generation and wastewater treatment. However, many of the studies are still primarily feasible only on a laboratory scale, and significant work is needed to launch the practice to an industrial level. Moreover, an unbalanced nutrient profile, such as the inadequate amount of nutrients and toxicity caused by ammonia and the large amounts of suspended solids in wastewater, can hinder suitable algal growth (Li et al., 2021) and lipid productivity (Chang et al., 2018). Wastewater must therefore be pretreated before cultivating microalgae.

As shown in **Figure 1**, strategies such as microalgae cultivation in combination with aquafarming, the simultaneous production of biodiesel with other VAPs, and integrating microalgae cultivation with other treatments such as biogas upgrading and wastewater treatment could prove to be efficient ways to lower the production cost of microalgae-based biodiesel. However, many aspects remain to be evaluated properly and incorporated into the process cost analysis, such as: 1) the overall impact of microalgal-aquatic animal symbiosis in the growth of both microalgae and the aquatic life, accounting for the risk of overconsumption of microalgae and the impact of toxic compounds produced by microalgae on the aquaculture environment; 2) the importance of the VAPs produced, and the cost of extracting them; 3) the fully optimized performance level of anaerobic digester-autotrophic microalgal cultivation; and 4) the impact of toxic and harmful waste products present in wastewater on the cultivation and lipid accumulation ability of microalgae and the quality of biodiesel produced.

STRATEGIES TO INCREASE LIPID AND BIOMASS PRODUCTIVITY

Optimum lipid and algal biomass productivity for microalgal-based biodiesel production can be achieved through efficient microalgae cultivating systems. Primarily, two types of microalgal cultivation systems have been the subject of interest of academia and industry: photobioreactors (PBRs) and open raceway ponds (ORPs). For photoautotrophic microalgae cultivation, carbon must be delivered in the form of carbon dioxide (CO_2) as the diffusion of atmospheric CO_2 hinders the growth of microalgae (Chisti, 2013). ORPs, otherwise known as high rate algal ponds, are cost-effective, low energy culturing methods (Show et al., 2017) that are constructed with depths of 20–50 cm to ensure adequate penetration of sunlight for enhanced biomass production. However, the efficiency of ORPs is significantly affected by various factors, such as a requirement for a large area of land, the influence of variable weather conditions, high water loss due to evaporation, inefficient light utilization, and susceptibility to predation and contamination by other microbes (Viamajala et al., 2016; Chu and Phang, 2019).

Photobioreactors, often referred to as closed cultivation systems (Siddiki et al., 2021b), address the drawbacks of ORPs by allowing the control of parameters and being designed to the specific needs of the microalgal strain of interest. For instance, PBRs require a relatively small area for operating, are less likely to run the risk of contamination, and can fully optimize light availability due to the use of artificial sources. A study conducted by Murray et al. (2017) showed that a PBR with free-flowing, submerged, wireless light sources used for growing *Chlorella vulgaris* and *Haematococcus pluvialis* was five times more efficient in light utilization than conventional lighting methods. This kind of lighting system also improved the uniformity of light provision and reduced the appearance of dark zones and the impacts of self-shading. Nevertheless, using PBR for culturing microalgae has some major challenges, such as overheating, problems related to cleaning and maintenance, biofouling, the proliferation of benthic algae, accumulation of dissolved oxygen which can hinder algal biomass productivity, and most importantly, the high expense in designing and operating the system (Chisti, 2008). Such expensive production costs hinder the ability to exploit economies of scale by increasing the reactor size to produce greater amounts of biodiesel (Kunjapur and Eldridge, 2010).

Development in photobioreactor designs to increase energy efficiency and allow a better exchange of gas and light is necessary to lower production costs (Morweiser et al., 2010). The oceans offer a great ground for establishing PBR systems as oceans dispense large cultivation areas for microalgae, with waves as efficient mixers and the seawater's high heat capacity as temperature regulators. Kim et al. (2016) found that a PBR system cultivating *Tetraselmis* in a partially continuous method attained a productivity of 3.9 $gm^{-2}\,day^{-1}$ biomass and 544.4 $mgm^{-2}\,day^{-1}$ fatty acid methyl ester. Operating PBRs with continuous cultures tends to be more efficient, which can result in high biomass productivity (Mata et al., 2010). However, PBRs with continuous cultures cannot be used to produce biodiesel via deliberate nutrient deficiency. Newer designs need to consider factors like nutrients, CO_2, light and water supply, oxygen removal, and maintenance of correct temperature and pH (Borowitzka and Vonshak, 2017).

The selection of appropriate cultivation techniques and the planning of their design depends on specific needs (Narala et al., 2016). For example, ORPs utilizing wastewater can be designed circularly or in a way the exploits gravitational flow, while pharmaceutical and nutritional products can be yielded using tubular PBRs. A biofilm cultivation system used to grow *Botryococcus braunii* was found to yield high quantities of biomass and lipids rich in long-chain hydrocarbons (Wijihastuti et al., 2017). Biofilm culturing provides the advantage of low energy needs and avoids much of the costs required for harvesting and dewatering processes. To make the supply of CO_2, nutrients, and water cheaper, PBRs and ORPs are often constructed near a combustion industry (Hanifzadeh et al., 2018). However, the cultivation of microalgae in flue gas can introduce additional costs related to gas pretreatment, storage, and pumping (Chisti, 2013).

Alternatively, carbon can also be provided in the form of bicarbonate (HCO_3^-) to culture those species of microalgae that are able to utilize this form of carbon (Hanifzadeh and Viamajala, 2014). Chi et al. (2011) recommended the development of a bicarbonate-based carbon capture for CO_2 as HCO_3^- to be later supplied to a microalgae culturing system. This bicarbonate-based carbon capture integrated microalgae production system has low production costs, due to the efficiency in absorption rate of atmospheric CO_2, and also generated high biomass productivity during cultivation (Canon-Rubio et al., 2016). Contamination and predation were also less likely as this method can induce alkalinity in the media and is therefore appropriate only for species that are tolerant to highly alkaline growth media.

Hanifzadeh et al. (2018) demonstrated that when HCO_3^- is supplied in ORPs cultivating *Chlorella vulgaris*, 50% higher algal productivity was reported (23.55 $gm^{-2}\,day^{-1}$) compared to conventional cultivation methods using CO_2. They found that the proposed method reduced the cultivation and energy cost by more than 55% and 80–90% respectively. On the other hand, the regulation and optimization of process parameters are crucial to enhance lipid productivity. The use of optimum temperature and pH, supply of adequate CO_2, exposure to nanoparticles, and induction of metal, nutrient, oxidative, and salinity stress can also affect biomass and obtain maximum lipid production, but the effect of each factor can vary from strain to strain (Sibi et al., 2016; Alishah Aratboni et al., 2019). Attributed to advancements in synthetic biology, a novel way of genetic modification of microalgae to improve lipid productivity has been garnering significant attention recently (Alishah Aratboni et al., 2019; Shokravi et al., 2020).

In order to address the limitations of both ORPs and PBRs, hybrid systems integrating both cultivation methods can maximize both algal biomass and lipid productivity. In hybrid systems, microalga is first cultivated in PBRs with sufficient supplies of nutrients to induce high algal growth and biomass productivity (Kunjapur and Eldridge, 2010). The matured algae are then shifted to ORPs and subject to nutrient stress to promote lipid production. Hybrid systems have previously been used in the US to produce *Haematococcus pluvialis*, which produced more than 420 $GJha^{-1}$ of microbial oil per year (Huntley and Redalje, 2007). *Arthrospira platensis* cultivated in a hybrid system was also found to increase the neutral lipid contents from 19 to 36.6% dry weight (Chernova and Kiseleva, 2017). In the first step, *A. platensis* was grown in a Zarrouk medium in a PBR under optimal conditions, and was then grown in ORPs under partially optimal conditions, aerated with 2% CO_2, and put under nutrient stress. Narala et al. (2016) developed an efficient two-stage cultivation system integrating positive pressure airlift controlled photobioreactors with a nutrient-deprived ORP for *Tetraselmis* sp. M8 displayed substantially high productivity of algal lipids compared to conventional standalone systems and also had a lower chance of contamination.

ECONOMIC ANALYSIS OF MICROALGAE-BASED BIOREFINERY

Biodiesel can serve as a cost-effective alternative to fossil-based diesel. In 2018, on average, biodiesel was priced at \$3.55 per gallon, while petrochemical diesel was priced at \$3.24 per gallon (U.S. Department of Energy, 2018). A preliminary economic analysis of the prospects of microalgal-based biodiesel revealed that biodiesel production cost is \$2.29/kg, compared to \$1.08/kg for petroleum diesel in the Hubei province (Sun et al., 2019). Unfortunately, higher operational and production costs are major hurdles for commercialization, and in many instances, microalgae-based biodiesel can cost more to produce than fuel from conventional sources (Branco-Vieira et al., 2020), depending on the scale of production, the processes used, and the biomass and lipid content produced (Desjardins et al., 2020). With a discounted rate of 7.34%, a negative net present value of \$26 million and an internal return rate (IRR) of 0.38% were attributed to the high capital investment (\$55.6 million). Despite the low profit, an annual benefit of \$4.82

million was recognized from revenues generated via biodiesel, animal feed, and electricity.

Even though PBRs have been used widely to grow microalgae, particularly for the treatment of wastewater from different sources, high investment costs and energy consumption hinder full-scale applications. The highly sophisticated material and technology requirement for constructing PBRs can mean equipment and installation costs makeup 65–75% of the total microalgae production cost and can be significantly costlier than other methods (Han et al., 2019; Li et al., 2021). The estimated cost for the production of microalgae biomass in a small-scale facility on 15 ha of land is €2.01/kg and for biodiesel, it is €0.33/L, with an EBIDTA (Earnings Before Interest, Taxes, Depreciation, and Amortization) of €588,139/year and a return on investment of 10% calculated with a 10 years payback time, which is less cost-effective than fossil fuel production (Branco-Vieira et al., 2020). The plant scale also has a large impact on the cost, with large scale plants being more profitable than small scale plants, keeping other parameters constant. For instance, when annual biodiesel production increased to 100,000 tons from 10,000 tons, the cost of production was found to reduce from $8.1 to $6.3 (Chen Jiaxin et al., 2018).

On the other hand, ORPs, first designed by Oswald in the 1960s (Oswald and Goleuke, 1967), have a low capital cost of US$2000/ha (Villar-Navarro et al., 2019). Even though the effectivity of ORPs may be limited by process parameters and the formation of contaminants, they require little power to operate and offer easy maintenance (Shin et al., 2018). Moreover, with a lower annual operating cost of $37–$42.65 million and lipid yielding a cost of $13/gal, ORPs represent a more cost-effective microalgae cultivation method than PBRs, which have an annual operating cost of $55–$62.80 million and lipid yielding a cost of $33/gal (Chen, 2017). Therefore, the total cost of cultivating microalgae may range from $2–$15/kg using ORPs, compared with $32/kg employing PBRs (Kothari et al., 2017). When an operating lifetime of 10 years is considered, depreciation made up only 15% of the unit biodiesel production cost in ORPs, while it took up 60–80% for PBRs (Chen Jiaxin et al., 2018). As a result, the unit cost of biodiesel produced via PBR can be 2–10 fold that of through ponds with the same production capacity (Chen Jiaxin et al., 2018). In addition, a 10% rate of return can be achieved from ORPs if triglycerides are priced at $8.52/gal compared to $18.10/gal for PBRs (Rajesh Banu et al., 2020).

Other methods have also been investigated. For instance, the revolving algal biofilm system was developed to achieve higher land utilization efficiency and biomass productivity than the open raceway pond (ORP) (Gross and Wen, 2014). Moreover, using a scraper, it also provides a more cost-effective and environmentally-friendly method of harvesting microalgae compared with conventional methods (Christenson and Sims, 2012). Conventional harvesting methods, such as flocculation, filtration, and centrifugation cost $2,000, $9,884, and $12,500 per square hectometre, respectively (Chen, 2017). Nevertheless, the revolving algal biofilm system has a much higher investment cost than the ORP (Han et al., 2019). Similarly, one study revealed that even though the cultivation of microalgae using algal turf scrubbers had a lower biomass production cost of $510/tonne compared with the $673/tonne using ORP, the production cost of fuel was lower ($6.27/gallon) for ORP compared with algal turf scrubbers ($8.34/gallon) (Hoffman et al., 2017). The costs of producing microalgal-based biodiesel are presented in **Table 2**.

As seen in **Table 1**, production costs of PBRs are considerably higher than production by ORPs due to the associated installation and operations costs. Nevertheless, PBRs can promote the axenic status of the culture, and are therefore, more appropriate for the production of high value/low volume compounds like bioactive and pharmaceuticals compounds (Chang et al., 2018). In addition, with the harvesting with lipid production accounting for 90% of total energy demand and 20–30% of the total production cost, flocculation has been considered a low operational and energy cost in recent years, with an operation and energy cost of €0.1–0.6/kg and 0.1–0.7 k Wh/kg biomass respectively for closed cultivation (Muhammad et al., 2021; Vasistha et al., 2021). In particular, flocculation facilitated by other organisms (Mofijur et al., 2021), such as fungus (Chen J. et al., 2018) or natural coagulants (Li et al., 2020), can make for cost-effective recovery with costs as low as $0.825 and $0.037, respectively. Centrifugation and ultrafiltration are less widely used due to having a high energy demand and being cost-intensive (Rajesh Banu et al., 2020).

Dehydration/dewatering and the extraction of biodiesel ensue after harvesting. The cost of dehydration is derived from the use of energy and comprises the utility cost of the plant. The dehydration stage for ORPs has a high operating cost since the water is discharged in large amounts. Overall, the selection of different dehydration technology did not have a significant effect on the biodiesel production cost as most of the technologies had similar costs ($2.92–3.06/L biodiesel) (Chen Jiaxin et al., 2018). The high capital cost of solvents for the extraction process is also another major limiting factor in economical biodiesel production. The high cost of green solvents makes it especially difficult to shift away from using toxic solvents (de Jesus et al., 2019b). In this regard, integrated approaches that utilize multiple kinds of solvents and combine physical methods can significantly reduce energy demand and cost.

Economic analyses of cultivation methods incorporating the cost-effect strategies discussed in the above section have been few, and most were done primarily for the co-production of VAPs. This is no surprise, as the global market for microalgae-based products is estimated to increase from $32.60 billion in 2017 to $53.43 billion in 2026 (Rahman, 2020). Gong and You (2015), with their proposed superstructure design for the simultaneous production of biodiesel and VAPs, namely, hydrogen, propylene glycol, glycerol-tert-butyl ether, and poly-3-hydroxybutyrate, found a biodiesel production cost of $2.79 per gasoline-equivalent gallon. Another study that used *Scenedesmus dimorphus* as a feedstock concluded that integrating reactive distillation with the biological oxidation of glycerol into the VAP dihydroxyacetone allows economically feasible biorefinery schemes for biodiesel production, with a net present value of approximately $2 million and an IRR of 19.8% (Tejada Carbajal et al., 2020). It was reported that the cost of biodiesel production could be reduced from $17.26/L to $13.73 US/L when protein is also extracted (Gupta et al., 2016). Other studies have revealed similar results (Bravo-Fritz et al., 2016). The cost of biodiesel production from microalgae was found to reduce from $3.90/L to a staggering $0.54/L when astaxanthin and PHB are co-produced (Prieto et al., 2017). Astaxanthin, a pigment

TABLE 2 | The total cost of producing microalgae-based biodiesel.

Cultivation (conventional)						References
Technique (conventional)	***Cost***					
	Capital ($million)	***Operating ($million)***	***Lipid yielding ($gal⁻¹)***	***Biodiesel upgrading ($gal⁻¹)***	***Biomass yielding ($kg⁻¹)***	
Open raceway ponds	390	37–42.7	6.3–13	9.84	0.7–15	Richardson et al. (2012); Chen. (2017); Kothari et al. (2017); Rajesh Banu et al., 2020
Photobio-reactors	990	55–62.8	33	20.53	32	Richardson et al. (2012); Chen. (2017); Kothari et al. (2017); Rajesh Banu et al., 2020

Harvesting			
Technique (conventional)	***Cost ($hm^{-2})***	***Energy (kwhm^{-3})***	
Flocculation	2,000	~0	Chen. (2017); Rajesh Banu et al. (2020)
Filtration	9,884	0.5–5.9	Chen. (2017); Rajesh Banu et al. (2020)
Centrifugation	12,500	3.29	Chen, (2017)

Dehydration			
Technique	***Capital Cost ($)***	***Operating Cost ($)***	
Solar/fixed bed drying	250,000	45,251	Chen, (2017)

Extraction		
Technique	***Solvent cost ($) to produce per kg of fatty acid***	
Soxhlet	5,947.90–27,345.98	de Jesus et al. (2019a)
Bligh and Dyer	860.02–7,469.2	de Jesus et al. (2019a)
Folch	1,548.44–6,382.75	de Jesus et al. (2019a)
Hara and Radin	167.22	de Jesus et al. (2019a)
Sonification and solvent (chloroform + methanol + water)	1.56	Ren et al. (2019)
Microwave and ionic liquid	50	Krishnan et al. (2020)

that can be produced by *Hematococcus pluvialis,* can be sold for $2,500/kg (Sathasivam et al., 2019) and currently has a market potential of $200 million because of its oxidant properties (Rajesh Banu et al., 2020).

Wu et al. (2018) investigated the economic optimization of microalgae-to-biofuels chains for producing diesel and ethanol simultaneously and found that the break-even prices of diesel and ethanol are estimated at about $0.49/kg and $2.61/kg, respectively, with an IRR of approximately 29.21% and a payback period of 3.25 years. Moreover, when biodiesel is produced with biogas, the cost is lowered from $72/L to $47/L (Harun et al., 2011). Notwithstanding, the most optimistic projections forecast the production of whole biomass utilizing the wastewater treatment strategy cost $0.73/kg dry weight (Acién Fernández et al., 2019). In particular, *Spirulina maxima* exhibits a great return on investment (86.92%) with a 99.3% purity of the produced biofuel when grown in wastewater treatment plants (Abdo et al., 2016).

Overall, the commercial prices and product yields play an important role in determining the profitability of such projects. Moreover, as observed, cultivation through ORPs, harvesting by flocculation, and extraction via mixed solvents can help increase cost-effectiveness. Despite the importance that it receives, lipid content often does not significantly affect the parameter of cost estimation if the microalgae residues are assigned an economic value (Chen Jiaxin et al., 2018). Most importantly, the economic performance and feasibility of microalgae-based biodiesel and other biofuels are dependent on access to co-product markets with higher VAPs as high VAPs could produce better financial outcomes (Batan et al., 2016; Bielsa et al., 2016; Dutta et al., 2016). The economic feasibility and sustainability of microalgae-based biodiesel production depend on the technologies used, which currently require significant technological innovation and development on an industrial scale. Therefore, policy measures that incentivize research and development, production, and consumption of microalgae-based biodiesel are important to reduce the large production cost gap that persists between biodiesel and petroleum diesel.

CONCLUSION

Numerous hurdles related to the cost of current technologies have restricted the widespread commercialization of microalgae-based biodiesel. Nevertheless, cost minimization strategies such as the cultivation of microalgae with aquafarming, in wastewater, or with biogas upgrading, and the co-production of VAPs have exhibited great promise in not only making the processes feasible but also in generating profits from co-products, thereby revealing a favourable economic platform for biorefinery scheme feasibility and profitability. Specifically, the cost of producing microalgal biodiesel can be lowered down to $0.73 kg^{-1} dry weight when cultivated in wastewater or $0.54 L^{-1} when co-produced with VAPs. Moreover, cultivation through ORPs, harvesting by flocculation, and extraction using mixed solvents can help increase the cost-effectiveness. While it is promising that corporates and governments have provided large investments in this field, stringent and well-planned policies and subsidies are necessary for the growth of the microalgae biodiesel industry.

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NR- Original draft; SA- Supervision, review and editing; IB-Review, editing and funding; MM- Review and editing; SK-Review and funding.

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