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Review article

Algae cultivation systems integrated with photovoltaic cell: A systematic review

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ABSTRACT

Microalgae species have recently been focused on biofuel production, such as biodiesel, bioethanol, and biohydrogen. These photosynthetic organisms are widely cultivated in photobioreactors and open ponds. Advances in the cultivation methods, e.g., the development of the open pond-photobioreactor hybrid system, floating, photobioreactor, open pond-photovoltaic, and photobioreactor-photovoltaic are aiming to overcome the limitations of both methods. Among the improvements achieved are lower energy cost due to lower dependency upon electricity from the grid, lesser greenhouse gas emissions, lower raw material cost due to lower evaporative water loss, higher algal biomass productivity, reduced biofouling, easier process control, and the ability of wastewater treatment. However, the systems are also limited by the variation in biomass productivity in different locations and environmental conditions. With further optimization studies, the environmental, economic, and energy aspects of open pond-photovoltaic and photobioreactor-photovoltaic systems can be improved. Overall, the open pond-photovoltaic system offers more diverse benefits than the photobioreactor-photovoltaic system. Nevertheless, both systems are practical for enhanced microalgae cultivation systems due to the fact that the quality, price, and product developments from both methods are different. This paper presents the development of modified open and closed algal cultivation systems, including the integration with photovoltaic cells.

1. Introduction

The rising global energy demand, coupled with climate change and the heavy reliance on fossil fuels, has been a significant challenge since the Industrial Revolution [1–5]. The burning of fossil fuels for energy production releases greenhouse gases and other harmful pollutants, such as carbon monoxide, carbon dioxide, nitrogen oxides, sulfur dioxide, methane, and volatile organic compounds (VOCs). In response, there is a global shift toward renewable energy sources—such as wind, solar, biomass, and hydropower—to mitigate the environmental impacts of fossil fuel consumption [2]. Additionally, the volatility of fossil fuel prices, driven by factors such as pandemics (e.g., COVID-19), geopolitical events, supply and demand imbalances, and infrastructure challenges, has further motivated the transition to cleaner energy alternatives [6–9].

Microalgae are a promising biomass source for biofuels and bioproducts, commonly cultivated in open ponds and photobioreactors (PBRs) [10]. Open pond systems are widely practised due to their low installation, operation costs, and energy use, and they can yield 10–20 times more biomass than conventional biodiesel crops [11]. These photosynthetic microorganisms rapidly accumulate lipids and proteins, making them suitable for various applications. However, open systems are vulnerable to contamination, weather fluctuations, and predation and require large land areas. To improve control over growth conditions like pH and temperature, PBRs are used to achieve higher biomass productivity [12,13]. While more efficient, PBRs involve higher costs for installation, maintenance, and operational inputs such as aeration and temperature regulation [14,15]. Nonetheless, open ponds remain relevant, particularly for wastewater treatment, CO_2 mitigation, and non-food algae-based product production [16]. On the other hand, closed PBRs are employed to produce high-quality algal biomass for food and pharmaceutical products. The continuous culture in PBRs is also

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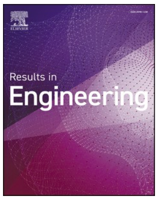

useful for higher biomass productivity and ensuring continuous raw materials supply [12]. The improvement of both open and closed systems is essential for better algal growth rate, biomass yield, cost-effectiveness, sustainability, and being environmentally friendly.

Among the initiatives to improve both systems include the integration of renewable energy to power algal cultivation. Simultaneous electrical and chemical energy generation is achievable through the integration of algal pond and photovoltaic cells at experimental and pilot scales, as demonstrated by previous studies [11, 17–26]. However, algae culture in the open pond is recognized to be vulnerable to contamination, e.g., protozoans, mosquito larvae, viruses, fungi, and bacteria [27]. Hence, the development of a hybrid open pond-photobioreactor at experimental and pilot scales has been noted to improve the growth rate and biomass productivity of microalgae by diluting the oxygen, heat, biofouling, and other cell growth inhibition factors inside the PBR into the open pond [28,29,12]. Unlike an open pond, a closed system in PBR minimizes this issue despite the high manufacturing and operating costs. Integration of photovoltaic cells aims to power the mixing and LEDs in an open pond case, while in this paper, the electricity generated is targeted to provide a shading effect to the PBR and to power the agitation and bubbling of CO_2, as well as the monitoring sensors. In addition, the marine floating PBR development is also gaining tremendous attention due to the installation performed on the surface of water bodies such as oceans without the use of land. Hence, free mixing energy of the culture is achievable from wave energy and the cooling effect of the large surrounding water body [14].

The integration of renewable energy, such as solar energy, in this paper, is essential to reduce operational costs, leading to cheaper biofuel production, reducing dependency on fossil fuels for electricity generation, lessening environmental impacts of fossil fuels burning, and long-term global energy cost stability [30,31]. Grid electricity costs are minimized via less or eliminated grid electricity usage for the operation, such as for mixing, lighting, aeration, and temperature regulation. In the case of using solar energy, photovoltaic cells require no fuel and almost zero maintenance [32]. For floating marine photobioreactors, wave energy substitutes the energy used for mixing the culture [33]. Photovoltaic cell integration is also advantageous in providing shading and light filtration while generating energy. In the long term, the utilization of photovoltaic cells is more economically efficient, as denoted by the levelized cost of energy (LCOE) compared to fossil fuels. Additional costs related to carbon emissions, such as carbon tax and emissions trading, are minimized when using renewable energy instead of fossil fuels [8].

In terms of society, the public energy burden is reduced by the reduced overall costs of microalgae-based product production. Lower renewable energy and its by-product costs, as well as minimized reliance on fossil fuels, could be achieved [32]. Besides being affordable, a more sustainable energy supply from abundant and free solar energy provides community access to locally generated renewable energy. From a health perspective, reduced fossil fuel burning translates into fewer harmful greenhouse gas emissions, resulting in better public health [34]. Microalgae also absorb carbon dioxide, contributing to climate change mitigation [35]. Many industries could also be greener and more cost-efficient as microalgae are employed in various sectors, such as wastewater treatment, energy, agriculture, pharmaceuticals, and food [30,35,36]. Job opportunities creation and economic development are achievable via further exploration of renewable energy in microalgae cultivation. Long-term cost stability is promising in using solar energy as it offers a forecastable long-term cost that could aid in fighting economic shocks associated with fossil fuels' cost fluctuation [37].

This paper presents an overview of the improvements performed on both open and closed algal cultivation systems in outdoor and indoor applications, including the integration of a photovoltaic system. The improvements include lower environmental impacts in terms of reduction in reliance on fossil fuels, lower capital and operation costs of microalgal cultivation, higher yield and better quality of microalgal biomass [10]. Novel cultivation methods that could result from the improvements include algae-PV in open ponds and photobioreactors with different setups and orientations to suit the cultivation conditions of different microalgal species.

2. Review significance and methodology

The literature review is considered a crucial phase in establishing a research area because it helps in determining and bridging gaps in a specific research field. A systematic literature review (SLR) is a process that permits the collection of related evidence on the given topic that fits the pre-specified eligibility criteria to answer the formulated research question [38]. Over the last 40 years, scientists have reported extensive results on algae cultivation systems; however, limited attention has been given to algae cultivation systems integrated with photovoltaic cells. The current study reviews the works performed by previous researchers and engineers and identifies the key areas that need further investigation towards the development of an algae cultivation system integrated with photovoltaic cells.

Well done SLR procedures ensure only relevant articles are taken into consideration by implying the three steps of SLR: (1) identification of keywords and their synonyms, (2) screening of database search results using the online filter tool based on the suitable criteria, and (3) eligibility of articles via manual screening. The search was done using the search string ("microalgae" OR "algae" OR "isochrysis") AND ("photobioreactor" OR "floating photobioreactor") AND ("photovoltaic" OR "solar panel" OR "agrisolar" OR "agrivoltaic"). These steps resulted in 90 papers that were included in the review. The reviewed bibliographies in this paper include the articles published in peer-reviewed international journals obtained from well-referenced databases, namely Scopus, Dimensions, and Google Scholar. The final set of this manuscript was further classified based on (i) general characteristics of algae, (ii) algae cultivation methods, (iii) algae cultivation system integrated with photovoltaic cells, and (iv) potential of algae cultivation system integrated with photovoltaic cells from the perspective of the environment and economic. At the end of the analysis of each relevant article, inferences were noted, and research gaps were identified.

3. General characters of algae

Algae are photoautotrophic and heteroautotrophic organisms that exist as red algae (Rhodophyta), brown algae (Rhaeophyta), and green algae (Chlorophyta) that can be further classified as macroalgae (seaweeds) and microalgae, according to their sizes [39]. Macroalgae are large algae, multicellular, and are visible to the naked eye, while microalgae are single-cell organisms. They can be easily found growing in a wide range of aquatic habitats, e.g., freshwater (lakes, rivers), saltwater (oceans), brackish water (mangrove swamps), and wastewater [40]. Microalgae, being the topic of interest in this review paper, are photosynthetic autotrophs that are commonly cultivated for their various benefits, e.g., high lipid, vitamins, and bioactive compound contents, making them excellent candidates for various product developments [41]. These organisms could make renewable and sustainable raw materials for microalgae-derived products that are available worldwide in the form of pharmaceutical and nutraceutical products, cosmetics, animal feed, fertilizer, and biofuel [42]. These versatile organisms are also applied in wastewater treatment and carbon dioxide sequestration [35]. Hence, researchers are making efforts to make microalgal cultivation sustainable, environmentally friendly, and cost-effective. These include advances in the algal cultivation system practices, e.g., developing the hybrid open pond-photobioreactor system, floating photobioreactor, indoor open pond, and integration of photovoltaic cell with algal open pond and photobioreactor.

4. Hybrid algae cultivation methods

Microalgae are grown in phototrophic cultivation mode, where light is used as a source of energy and inorganic carbon as the source of carbon [43]. Mass cultivation of photosynthetic algae is performed worldwide in open ponds and photobioreactors (PBRs).

4.1. Open pond

Microalgae productivity varies with the location, cultivation system, local climate, and algae species [44]. Microalgae cultivation in open raceway ponds was the first mass algal cultivation system that was attempted in 1988, and extensive research on scaling up algae cultivation has been ever since [12]. The known advantages of open pond methods are minimal start-up and operating costs and low energy requirements for mixing and aeration of the culture [45]. Microalgae in open ponds grow under diurnal light and temperature while consuming CO_2 and nutrients and releasing O_2. This requires submerged aerators and paddlewheels to be installed in open ponds for aeration and mixing purposes [44]. On the downside, this approach needs large areas for scaling up, and the algal culture is exposed to contamination and extreme weather conditions [46]. Control over cultivation conditions, temperature, pH, and evaporation rate are unachievable; hence, the cultivation needs to tolerate these diverse climate conditions [47,45]. Circular and raceway ponds and tanks are used in the cultivation of rapidly growing microalgae, such as *Chlorella* sp., and microalgae that are robust to extreme environments, such as *Spirulina sp* [48].

4.2. Photobioreactor (PBR)

On the other hand, photobioreactor (PBR), a closed algal cultivation system with higher quality and efficient operations, take place in highly controlled conditions, dodging the limitations of open pond cultivation [12]. PBRs provide a controlled and closed environment; hence, they are used for the cultivation of microalgae that are sensitive to environmental conditions and apt for biological contamination. PBR is adequately designed and optimized to fulfill the requirements of the strains of choice that utilize little space with high light accessibility and significantly lower contamination issues [49,50]. However, this innovative PBR is also limited by several issues, mainly high manufacturing and operating costs, biofouling, and the high buildup of dissolved oxygen that results in limited growth and overheating. Lighting is a crucial design parameter for a PBR since it restricts the geometry, affecting the surface/volume ratio (S/V) [51]. There are different types of PBR available, e.g., tubular, flat panel, airlift, hybrid, and floating [51,12,52,33] with tubular PBR being the most commonly used [53]. PBRs are of different designs (flat plate and tubing) and configurations (vertical, horizontal, and inclined); however, the energy consumption for facilitating the mass transfer and sustaining algal cells in suspension contributes to 31 % of the production cost despite the PBR design [48,50].

4.3. Hybrid system

Hybrid cultivation systems that combine open ponds and photobioreactors (PBRs) have gained attention as a practical approach to improve microalgae productivity. The hybrid system was developed for the cultivation of *Scenedesmus dimorphus*, whereby the culture circulates inside the system, controlled by a pump, as shown in Fig. 1. The integration of these two algal cultivation methods dilutes the oxygen, heat, biofouling, and other cell growth inhibition factors inside the PBR into the open pond [28]. This 5-L working volume system has improved the biomass productivity compared to open pond and PBR as separate units by 74.3 % and 12.5 %, respectively. The hybrid setup reduced issues like overheating and oxygen accumulation, resulting in more stable and efficient growth conditions. This enhancement was due to the balanced conditions provided by the hybrid setup, which helped maintain optimal temperature and pH while improving nutrient use and growth stability. Similarly, Penloglou et al. [54] reviewed multiple PBR designs and emphasized that hybrid integration can provide better light distribution, temperature control, and flexibility, especially for biofuel and wastewater applications.

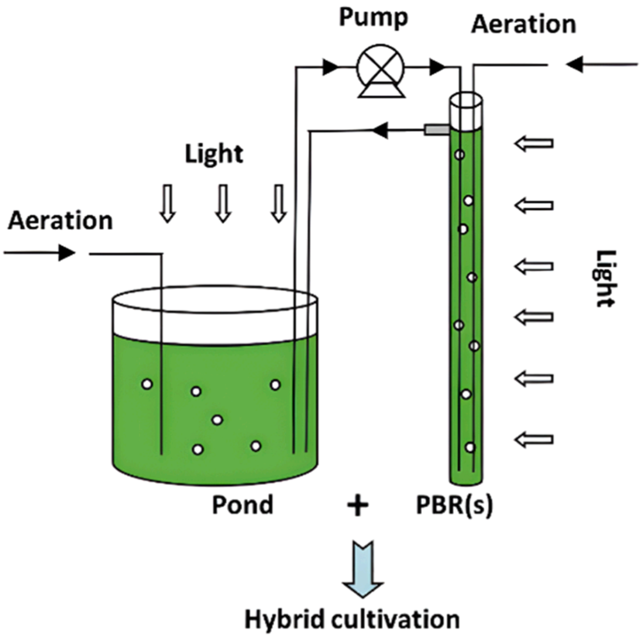

Fig. 1. Scenedesmus *dimorphus* cultivation in hybrid system as reported in Liu et al. [28], Elsevier.

A two-stage hybrid cultivation system was developed and tested for the cultivation of *Tetraselsmis sp*. by transferring at least half of the 19-L portion of the rapidly growing algae culture from PBR to the open pond. This stimulates lipid biosynthesis and accumulation by nutrient depletion, making the culture ready for the harvesting process [12]. The growth rate and biomass productivity in this hybrid system were found to be higher than those of a single raceway pond and PBR system. Similarly, Yun et al. [55] found that a 60-L hybrid PBR-open pond setup using wastewater feedstock increased algal biomass and lipid productivity by 40 % and 62 %, respectively. Penloglou et al. [54] supported these findings, stating that hybrid systems enhance light use efficiency and environmental stability, making them well-suited for biofuel and wastewater treatment applications.

Despite these promising outcomes, hybrid systems still face several challenges. Liu et al. [28] noted that the system requires careful coordination of nutrient flow, light, and circulation, which increases operational complexity. Narala et al. [12] highlighted issues with scalability, especially in outdoor conditions, where contamination and weather variability can affect performance. Yun et al. [55] raised concerns about nutrient inconsistencies when using wastewater, which can influence algal growth stability. Penloglou et al. [54] also mentioned that energy consumption for mixing and temperature control can be high, and further technological improvements are needed to lower costs and simplify system automation. Overall, while hybrid systems offer clear benefits, more work is needed to make them reliable, energy-efficient, and cost-effective for large-scale use. A comparison between PBR, open pond, and hybrid systems is tabulated in Table 1 below.

Lipid-rich microalgae [12,55], high microalgal biomass productivity [28], and potential for biofuel production [54] are achievable via a hybrid system, which allows for separate cell growth and lipid accumulation phases. This enables the exponential growth of algae cells while efficiently avoiding contamination issues. From the performed studies, a hybrid system for algae cultivation is proven to be an alternative to address contamination issues in open ponds and high costs in PBR while concurrently producing lipid-rich algae biomass.

Table 1
Comparison of PBR, open pond, and hybrid system for algae cultivation [12].

Factor	Photobioreactor	Raceway pond	Hybrid system
Biomass quality	Reproducible	Variable	Reproducible
CO_2 sparging efficiency	High	Low	Moderate
Contamination risk	Low	High	Low
Energy input for mixing	High	Low	Moderate
Evaporation loss	Low	High	Moderate
Maintaining continuous exponential phase	Difficult	Difficult	Easy
Maintenance	Difficult	Easy	Moderate
Operation type	Batch	Batch	Continuous
Setup cost	High	Low	Moderate
Space required	Moderate	High	High

4.4. *Outdoor versus indoor cultivations*

The outdoor open pond is the most frequently used approach to open pond microalgae cultivation. Table 2 presents the outdoor open ponds developed for different microalgae species, aiming for different harvesting yields, e.g., biomass, lipid, carbohydrate, bioactive compounds, etc.

From Table 2, *Arthrospira platensis* is the most cultivated using the open pond method for carbohydrate production, as demonstrated by Liu et al. [57], Magro et al. [59], Mehar et al. [27], Prakash et al. [56], and Raeisossadati et al. [67]. Magro et al. [59] performed *Arthrospira platensis* cultivation with 10 L working volume and achieved the highest carbohydrate content of 72 %. Cultivations of *Chlorella* sp. microalgae are commonly aimed at high lipid biomass, as studied at pilot scale by Ribeiro et al. [64] and Yang et al. [66]; meanwhile, Dahmani et al. [62] explored the potential of *Chlorella pyrenoidosa* in secondary wastewater treatment. Similar to *Chlorella* sp., *Scenedesmus sp.* is also cultivated for the lipid, as studied by Eustance et al. [65], Koley et al. [61], and Ribeiro et al. [64] at pilot scale in 30.37 m^3, 40 m^3, and 2 m^3 working volumes, respectively. Li et al. [19] developed a 1 m^3 solar-powered open pond for the cultivation of *Nannochloropsis oceanica* that significantly reduced the biomass production cost compared to the traditional open pond at a similar performance.

Meanwhile, microalgae cultivation in photobioreactors offers higher and better-quality yields; however, the development is constrained by the high capital and operating costs. PBRs have been installed indoors and outdoors, depending on the type of PBRs used. Table 3 shows outdoor PBR types and their applications in algae cultivation.

Floating outdoor PBRs provide a lower cost of an algae cultivation system, as demonstrated in 20 L closed floating photobioreactors by Toyoshima et al. [73] and 50, 75, and 100 L membrane floating photobioreactors by C. Zhu, Han, et al. [74], with improved cell density found by Zhang et al. [68] and reduced biofouling as demonstrated by Kim et al. [70]. Novoveská et al. [71] developed a floating PBR that combined biofuel production with wastewater treatment at a low cost. This is due to the utilization of waves in coastal areas as free energy for mixing the algae culture. The developed PBRs resulted in improvement in biomass productivity, e.g., Thin-film flat-plate PBR and tightly-controlled turbidostat-based PBR [72,69]. Fig. 2 depicts the developed floating outdoor PBR by [73] and [14].

The open pond method is more synonymous with outdoor cultivation, but it has the known limitations of lower yield and contamination. These features have been improved via the development of solar-integrated open ponds and indoor open ponds. Wim and Rommie [75] conducted a pilot-scale study of two sets of open ponds: (1) indoor in a glasshouse and (2) outdoor with a working volume of 150 m^3 each. Different findings were found for both open ponds, with the indoor open pond having higher harvest efficiency compared to the outdoor pond. This was due to the different compositions of algae species found in both open ponds. It was noted that the indoor pond comprised a higher composition of bigger algal species (*Scenedesmus* sp.), while the outdoor open pond was richer in the smaller *Chlorella* sp. species. The indoor pond also demonstrated less heat consumption throughout the one year of study, with <40 % heat requirement during summer. Meanwhile, for outdoor open ponds, heating was essential almost all year long, except for some duration during summer. Despite the advantages of the indoor open pond, it necessitated almost triple the water supply compared to the outdoor pond, which contributed to the increment in the operating cost. The summary of the study's findings is presented in Table 4 Wim and Rommie [75].

Table 2
Open pond types and their applications in algae cultivation.

Open pond types	Algae species	Findings	References
Open raceway pond	*Arthrospira platensis, A. maxima, D. salina, C. vulgaris and H. pluvialis*	• Suitable for production of astaxanthin.	[56]
Open raceway pond	*Chlorella pyrenoidosa* and *Arthrospira platensis*	• Significantly increased cell growth rate as well as biomass productivity.	[57,58].
Open raceway pond	*Arthrospira platensis*	• pH 8.5 was the best for biomass productivity, CO_2 bio-fixation rate, protein, and phycocyanin content.	[27]
Open raceway pond	*Arthrospira platensis*	• Highest carbohydrate content of 72 %.	[59]
Open raceway pond	*Arthrospira platensis*	• 44 % less cultivation area achieved for phycocyanin production.	[60]
Open and polyhouse raceway ponds	*Scenedesmus accuminatus*	• Potential for sustainable biodiesel production.	[61]
Open raceway pond	*Chlorella pyrenoidosa*	• Potential nutrient removal by algae cultivated in secondary wastewater.	[62]
Open raceway pond	*Spirulina* sp. (208 and 220)	• The two strains can be utilized for biomass production and CO_2 mitigation.	[63]
Open raceway pond	*Chlorella* sp., *Coleastrum sphaericum, Scenedesmus acuminatus, Scenedesmus spinosos, Coleastrum sphaericum, Pseudokirchneriella subcapitata*	• *Coelastrum* sp. and *P. subcapitata* have highest lipid content, about 20 % of dry mass.	[64]
Open raceway pond	*Scenedesmus acutus*	• Increased lipid productivity by reducing cultivation depth and nitrogen concentrations.	[65]
Open raceway pond	*Chlorella mutant PY-ZU1*	• Microalgal biomass yield increased by 18 %.	[66]
Solar powered open pond	*Nannochloropsis oceanica*	• Suitable for aqauaculture feed. • Production cost significantly reduced. • Productivity of biomass similar to traditional open pond.	[19]

Katerina et al. [76] investigated the performance of three pilot-scale indoor PBRs, multi-tubular (60 L), helical-tubular (170 L), and flat-panel airlift (25 L), in a greenhouse laboratory and reported that primary energy consumption came from the maintenance of light intensity for the flat-panel PBR and culture circulation in the helical-tubular PBR.

Table 3
Outdoor PBRs and their applications in algae cultivation.

PBR types	Algae species	Findings	References
Rotating floating photobioreactor (RF-PBR)	*Chlorella zofingiensis*	• Cell density was improved.	[68]
Thin-film flat-plate photobioreactor (FP-PBR)	*Chlorella* sp.	• High productivity of *Chlorella* sp.	[69]
Semi-permeable membrane floating photobioreactor (SPM-PBR)	*Tetraselmis* sp.	• Biofouling reduced by 40 %. • Biomass productivity was improved.	[70]
Floating photobioreactor (F-PBR)	*Enterococcus* sp.	• Combination of algal biofuel production and wastewater treatment is feasible.	[71]
Tightly-controlled turbidostat-based photobioreactors	*Neochloris oleoabundans* and *Scenedesmus dimorphus*	• Growths of both algae were enhanced.	[72]
Floating photobioreactor (F-PBR)	*Isochrysis zhangjiangensis*	• Low-cost microalgae production system.	[13]
Floating photobioreactor (F-PBR)	*Arthrospira platensis*	• Low-cost microalgae production system	[73]

Flat-panel PB demonstrated approximately 8 times the energy consumption higher than the multi-tubular PB; however, the multi-tubular PB possessed the highest temperature sensitivity among all studied PBRs, leading to a significant decline in *Chlorella pyrenoidosa* during warm summer. No significant variation in the biomass and lipid yields was found from all three types of PBR, and multi-tubular PBR was chosen to be the most appropriate for scaling-up purposes concerning the lowest energy requirement. It was noted indoor PBR might not be a suitable approach for microalgal cultivation during summer and in tropical areas. The same study suggested the development of a PBR-open pond hybrid system to fulfill the requirement of all year-long cultivation and harvesting in central Europe.

A semi-pilot scale of tubular closed PBR was developed to study the growth behavior of three microalgal species, *Chlamydomonas variabilis, Spirulina platensis*, and *Microcystis aeruginosa* [77]. The 48 L PBR was illuminated using white fluorescent lamps, and *Microcystis aeruginosa* demonstrated the best performance of all the cultivated species. The species was cultivated at room temperature, required the lowest light intensity and air supply, had no biofouling on the PBR's wall, did not necessitate CO_2 supply, easy to harvest, has the shortest retention time and simplest inoculum preparation, as well as exhibited the highest biomass productivity of 0.7 g dry biomass/L, which was 3 and 23 times higher than *Chlamydomonas variabilis* and *Spirulina platensis*, respectively. The authors reported the potential scaling up of the whole process with some advancements in the technology for improved biomass yield. Table 5 presents a summary of the study's findings.

Osama et al. [78] proposed the scaling down of the industrial PBR to a household, which is believed to improve the quality of indoor air by significant CO_2 level reduction, especially in enclosed buildings, e.g., offices, classrooms, and bedrooms in Egypt. The household PBR (H-PBR) can be installed outdoors or indoors with a capital start-up of less than \$200 and a monthly maintenance cost of less than \$15 for up to 100 L of PBR. Outdoor H-PBR can also be used for wastewater treatment, and a business model was built, showing the H-PBR could be profitable to the household algal farmers via selling the algal biomass, e.g., *Spirulina* sp., which has a good price in Egypt. In addition to CO_2 reduction, wastewater treatment, and revenue creation, this approach is seen to improve public health, create job opportunities, and encourage the Egyptians to live a more sustainable life. The high energy consumption constraints of the proposed H-PBR during the microalgae cultivation in the H-PBR and social acceptance of the newly introduced technology are believed to be

Table 4
Outdoor versus indoor open pond.

Open pond	Outdoor	Indoor
Biomass yield (kg dry weight/ year)	N/A	141
Heat consumption	Higher, required heating almost all year long	Lower, 40 % less heat consumption during summer
Harvest efficiency (%)	Lower than indoor open pond	20–60 % for flocculant dose increment from 1–4 g/m^3
Species composition	More *Chlorella* sp.	More *Scenedesmus* sp.
Water consumption (m^3/year)	450	1200

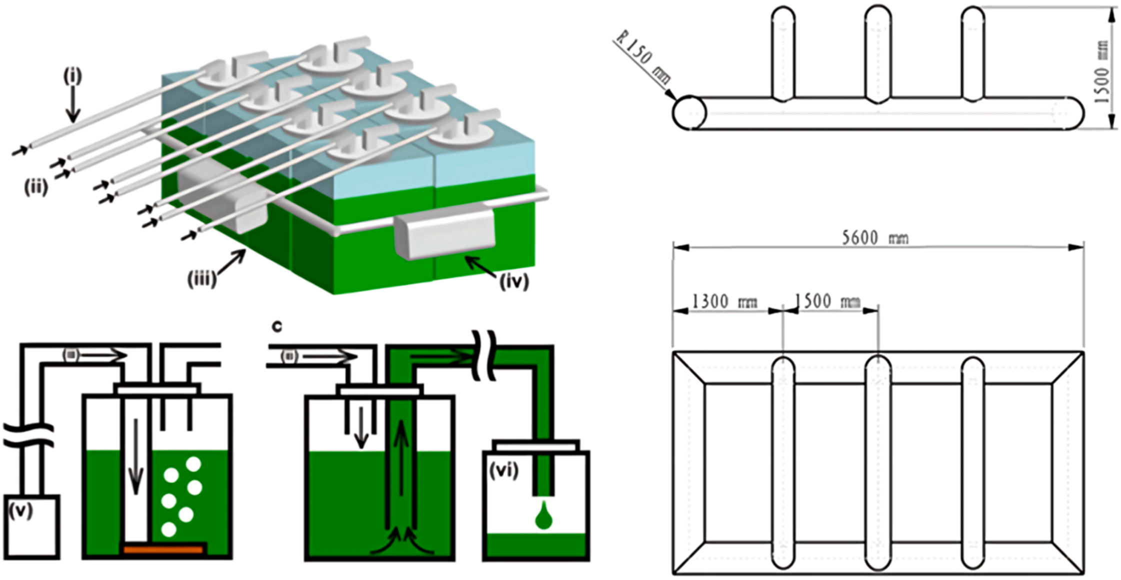

Fig. 2. Schematic representation of (a) floating photobioreactor developed by Toyoshima et al. [73]. (i) silicone tube, (ii) air inlet, (iii) polypropylene/polycarbonate container, (iv) float, (v) air pump, (vi) harvest tank and (b) inflatable floating membrane photobioreactor developed by C. Zhu, Han, et al. [74].

Table 5
Summary of microalgae cultivation in tubular closed PBR [77].

Parameter	*Microcystis aeruginosa*	*Chlamydomonas variabilis*	*Spirulina platensis*
Temperature (°C)	25 ± 2	25 ± 2	28 ± 2
pH	7.3–8	7.3–8	7.3–9
Light intensity (lux)	1500–2000	2500–3000	1500–2000
Growing media	BG11		
Retention time (day)	2	3	5
Inoculum	Supernatant of harvested culture	Part of harvested culture	Pre-stock culture
Cell attachment	No cells attached to reactor's inner wall	No cells attached to reactor's inner wall	Cells attached to inner reactor's wall and needed continuous removal
CO_2 supply	Not required		
Air supply (m^3/day)	50	50	63
Biomass productivity (g dry biomass/day)	0.7	0.03	0.26
Harvesting	Settling and centrifugation	Vacuum filter press	Settling and centrifugation

minimized via the integration of renewable energy sources to power the cultivation system and awareness creation on the innovative approach of the microalgae cultivation.

Sarker and Salam [79] cultivated *Chlorella* sp., in 100 m^3 outdoor PBR and 0.1 m^3 indoor PBR and reported a longer *Chlorella* sp. growth cycle in indoor PBR that contributes to higher energy consumption by 232 to 270 times in indoor PBR compared to outdoor PBR. The same study also noted more significant capital and operating costs for indoor PBR than outdoor PBR. pH control was easier in outdoor PBR, which also yielded 9 times higher biomass yield in comparison with indoor PBR. The outdoor PBR was tested for nutrient removal from housing wastewater and proved to perform better than wastewater treatment plants, with efficient elimination of BOD, COD, TKN, and TP, at 72 times more energy consumption than the conventional wastewater treatment plant. The study concluded that outdoor PBR performed better than indoor PBR, as summarized in Table 6.

The outdoor and indoor cultivation of microalgal species is discussed, and the summary is presented in Table 7 below. In sum, both outdoor and indoor cultivations in open ponds and photobioreactors have their pros and cons depending on the algal species, operating conditions, desired yields, etc. For instance, the open pond is more synonymous with outdoor cultivation, and a limited amount of literature was found on indoor open pond cultivation. However, indoor open ponds demonstrated better yield and lower energy consumption, which simultaneously overcame the disadvantages of low yield due to contamination, despite the higher operating cost due to the higher water requirement. Meanwhile, for PBR, tubular PBR is frequently used on a commercial scale; however, outdoor PBR, or floating PBR, is making a breakthrough due to its benefits, such as lower energy consumption, simpler design, lower biofouling, easier pH control, and cost reduction, eliminating the primary bottlenecks of PBR development. With further studies on the unknown parameters in floating PBR, together with the life cycle assessment (LCA) of the system, it is predicted to be the future of the microalgae cultivation approach.

Table 6
Outdoor versus indoor PBR [79].

Parameter	Outdoor	Indoor
Cycle (days)	4–6	10
pH control	7.0–8.0	7.5
Biomass yield (g/L)	0.0960	0.0131
Energy consumption (Wh/day)	4185–4847	18
Capital cost (THB)	9505	370
Operating cost (THB)	200–336	20–53
Nutrient removal efficiency from housing wastewater	100 % removal of BOD, COD, TKN, and TP	N/A

Table 7
Summary of outdoor and indoor cultivation of microalgae.

	Outdoor	Indoor
Open pond	Advantages • Diverse possible microalgal species cultivation. • Various yields, e.g., biomass, lipid, carbohydrate, lipid. • Lower operating cost. • Can be integrated with wastewater treatment. Disadvantages • Contamination by other microalgal and grazer species. • Low productivity.	Advantages • Higher harvest than outdoor open pond. • Higher composition of bigger microalgal species than smaller ones. • Less power requirement for heating than outdoor open pond. Disadvantages • Higher water requirement up to 3 times. • Higher operating cost.
Photobioreactor	Advantages • Floating PBRs are the most used. • Lower energy consumption. • Cost reduction. • Can be integrated with wastewater treatment. • Simple design. • Reduced biofouling. • Increased cell density and biomass productivity. • Easier pH control. • Better performance in wastewater treatment than indoor PBR. Disadvantages • Unknown hydronamics performance and inner liquid mixing in response to wave conditions. • Unknown potential environmental impacts at commercial scale. • Novel membrane materials are not yet developed.	Advantages • Multi tubular is the most appropriate for scaling up (lowest energy requirement). • Suitable for use during summer and in tropical areas. • Microcystis aeruginosa has highest performance in tubular closed PBR. • Household PBR (H-PBR) to improve indoor air quality. Disadvantages • Significant production decline during summer. • No significant biomass and lipid variations in different PBR types.

5. Algae cultivation integrated with photovoltaic cell

5.1. Photovoltaic cell

A Photovoltaic (PV) cell is a device used to harness solar energy and convert it to electricity. PV is classified into a few groups, e.g., silicon, crystalline, and thin-film, and each type has different efficiencies and applications [80]. Transparent PVs are making breakthroughs in PV technology via the development of new organic PV (OPV), perovskites, and dye-sensitized solar cells (DSC) that are suitable for window and agricultural purposes due to their transparency. Available PV cells in the market are able to convert sunlight to electricity at an efficiency of >20 % and are also favored by light intensities Barbera et al. [23,81]. High solar irradiance regions are appropriate for PV cell installation due to the fact that output electricity generation is influenced by the light intensity. PV cells are also used in agricultural applications, known as agrivoltaic (AV), and are available in Malaysia, France, Italy, the USA, and India [82]. The same study reported that the AV application in Malaysia offers additional monetary benefits to solar farmers, which consequently leads to supporting Malaysia's Green Economy, as evidenced by the Monte Carlo Simulation findings.

5.2. Open pond-photovoltaic cell integration

The development of open pond-photovoltaic cells is driven by the efforts to minimize extensive energy and productivity losses in algal ponds via better exploitation of sunlight to enhance biomass productivity with cogeneration of electricity Barbera, Sforza, Vecchiato, et al. [24,42]. The potential of microalgae as biofuel feedstocks is among the motivations for the improvements in the environmental and commercial viabilities of microalgae product development [23].

Microalgae are photosynthetic microorganisms, and the most effective light portions during photosynthesis are the red and blue spectra [67,83]. However, the photosynthetically active radiation (PAR) range is only 48 % of the sunlight, with blue and red spectra only making up 16 % of the portion [23]. The rest of the light spectra are reflected back and waste or could negatively impact algal cultivation in raceway ponds by heating the media, causing unnecessarily high evaporation rates [84,29, 23]. The study proposed a raceway pond-semi-transparent PV system for simultaneous algal biomass and electricity generation using red and blue light-emitting diodes (LEDs) and reported environmental and energy cost reduction. This supported the finding in Reza & Parlevliet [85] that using semi-transparent elements in greenhouses could reduce PAR, consequently reducing loss in plant production.

Reza & Parlevliet [85] proposed algal photosynthesis enhancement via the installation of solar panels above the algal culture in a raceway pond that functions as a filter to modify the light spectrum received by algae and diverting the unused light spectrum by the algae's chlorophyll for electricity generation. The generated electricity can be used to power additional lighting for the system, for instance, blue and red LEDs. The co-production of electricity by the crystalline silicon PV cells also provided cheaper and more efficient bioenergy production. The shading effect of the PV cells also minimized the water evaporation from the raceway pond, reducing the cost of water for the evaporated water compensation. The idea of integrating greenhouses and PV is well established in the photovoltaic greenhouses area, e.g., Building Integrated Photovoltaic (BIPV) systems that incorporate solar modules into the building [85,29] developed raceway ponds in a greenhouse powered by copper indium gallium selenide (CIGS) PV and performed life cycle analysis (LCA) of the integrated system. The study discovered the optimal 20 % percentage of PV coverture in terms of the algal growth and biomass production, as well as the economy and environment. This configuration successfully balanced light availability, biomass growth, and energy recovery, while also reducing the environmental footprint, such as greenhouse gas emissions and water loss through evaporation.

Li et al. [19] developed an open pond integrated with solar panels for the cultivation of *Nannochloropsis oceania* and reported a significant reduction in the culture cost due to the elimination of additional energy input. The 1000 L self-sustaining system also generated a high cell density *Nannochloropsis oceania* population with high protein and EPA content. The system is also easy to work with, providing a simple method of *Nannochloropsis oceania* cultivation for aquaculture and health applications. The schematic diagram of the system is shown in Fig. 3.

The integration of algal ponds with PV offers co-generation of electricity with algal biomass that minimizes the dependency upon conventional electricity and, in some cases, makes the algal cultivation system stand alone. Spectrum filtration and diversion also enhanced the photosynthesis rate of microalgae by supplying the only required spectra (blue and red) and utilizing the remaining spectra for electricity generation that could also be used to power LEDs. The overall cell density and biomass productivity also demonstrated improvements, which, in turn, resulted in reduced land use and a more cost-effective system. The shading effect of the PV also contributed to less evaporative pond water loss; hence, less water supply is required.

Nevertheless, the shading effect of PV is undesirable during winter when the light intensity is low, where less biomass productivity is obtained. In addition, the optimum PV coverture percentage varies with different locations and environmental conditions; hence, further optimization studies are essential for optimizing algal biomass yield.

Hamedani et al. [86] developed and tested a small-scale aquavoltaic system in which PV modules were installed above raceway ponds. Their design maintained favorable cultivation conditions by controlling dissolved oxygen, temperature, pH, and light intensity beneath the PV panels. The system allowed sustainable co-production of algal biomass and solar electricity, proving to be effective in regions with high solar irradiance. This work demonstrated that even small-scale installations could contribute meaningfully to energy-autonomous algal production units despite the need for optimization studies before scaling up the system. The open pond-PV system developed by Hamedani et al. [86] is shown in Fig. 4. The summary of all open pond-PV systems for algal biomass production is presented in Table 8.

5.3. Photobioreactor-photovoltaic cell integration

Recent advancements in microalgae cultivation have explored

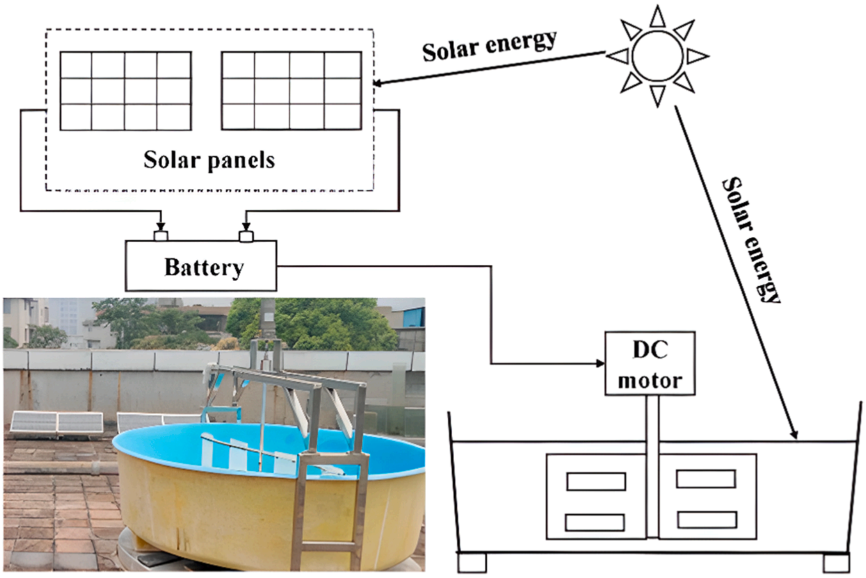

Fig. 3. Schematic representation of the open pond-PV system [19].

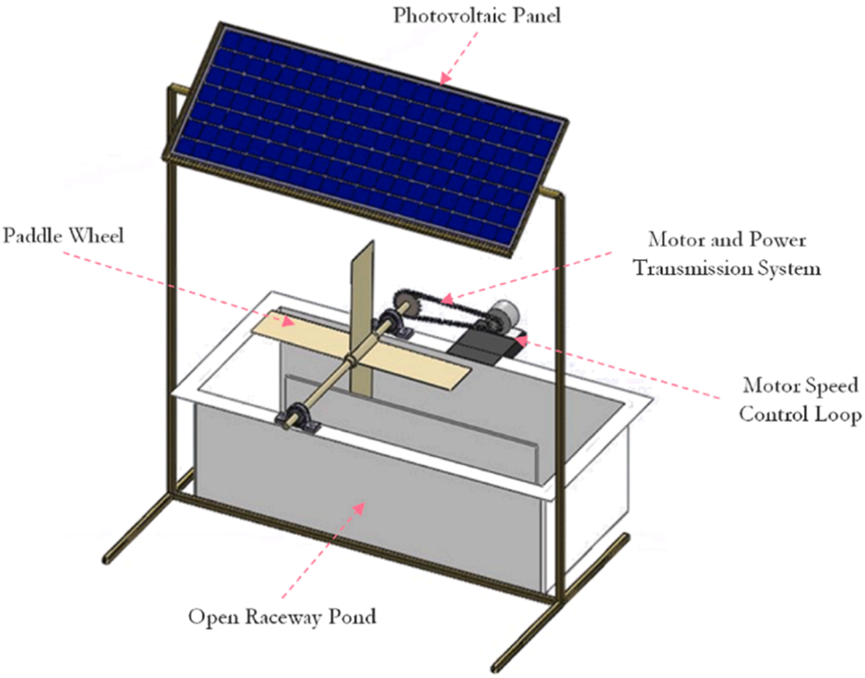

Fig. 4. Open pond-PV or aquavoltaic system developed by Hamedani et al. [86].

Table 8
Microalgae open pond-PV integration from the literature.

PV type	Microalgae species	Findings	Limitation	References
Semi-transparent PV	Microalgae	• Reduced land use • Enhanced microalgae cultivation process productivity • Reduced amount of water evaporation in raceway pond	• The system's economic viability (costs the PV system)	[23]
Crystalline silicon	Green algae	• Electricity generated can power additional illumination using LEDs • Cheaper and more efficient bioenergy production • Value added crop-filter • Reduced freshwater evaporation and filter light spectrum	• Luminescent solar concentrator (LSC) could be used for efficient solar spectrum use	[85]
Mono-crystalline silicon	*Scenedesmus obliquus*	• Enhanced biomass productivity under high irradiation (shading effect) decreased photoinhibition phenomenon. • Increased overall sunlight energy conversion efficiency • Electricity produced able to self-sustain the process • Faster return of investment (ROI) of the PV installation • Improved economic potential of coupling PV with raceway ponds in greenhouse	• Optimization of number and disposition of PV modules on the greenhouse roof • Development of a pilot plant	(Barbera et al., 2017)
Copper indium gallium selenide (CIGS)	*Chlorococcum sp.*, *Desmodesmus sp.*,	• 20 % coverture of PV panels was the best from energetic and environmental point of view • PV shading is beneficial during hot summer and vice versa during cold season	• Challenging to sustain a profitable production from an economic point of view, despite the increased processes technicality.	[29]
Not specified	*Spirulina* sp.	• Low-cost, sustainable, standalone system achieved. • Shading effect helps reduce evaporative water loss, reduce water temperature fluctuation, provide more stable environment for *Spirulina* sp. growth. • 7 % reduction in electricity cost.	• Optimization required for scaling up. • High reliance on solar, power produced vary with weather. • Limited comparison with non-algae-PV system.	[86]
Not specified	*Nannochloropsis oceania*	• Culture costs significantly reduced than traditional culture techniques • Generated high cell density microalgal population with high protein and EPA content • Easy method to work with • Simple technique to be used in *Nannochloropsis oceania* cultivation for aquaculture and health purposes	• Operating temperature was lower than optimal temperature for *Nannochloropsis oceania* growth	[19]

photovoltaic (PV)-powered photobioreactors (PBRs) as promising alternatives to conventional systems. The effect of the integration of PV with PBR is still under intense investigation [42]. PV-integrated PBRs offer dual benefits by producing biomass while also generating electricity, thus improving energy efficiency and sustainability. Jin et al. [87] developed and reported the integration of PBR-PV with anaerobic and aerobic systems to form a microalgae bio-loop. A standalone system was successfully established that subsequently resulted in the reductions of environmental impact and total investments of 75 % and 84 %, respectively. Dye-sensitized cell PV used by Barbera, Sforza, Guidobaldi, et al. [81] yielded improved light energy utilization as well as enhanced microalgal biomass productivity. In another work, Sforza et al. [22]

reported that during high irradiances, reduced photoinhibition and improved biomass productivity were achieved, while at night time, similar productivity was found with that of PBR without PV. A recent experimental study on small-scale hybrid systems that combine solar photovoltaic panels with microalgae cultivation has shown promising results, successfully producing both energy and algal biomass at the same time [86]. Similar findings were found by Barbera, Sforza, Vecchiato, et al. [17]. In addition, a positive impact on cost-effectiveness was proven by the faster return on investment (ROI) with PV installation. *Scenedesmus obliquus* cultivation in PBR-PV resulted in the co-production of lipid and protein [88].

However, these systems also introduce new challenges, including structural complexity, higher initial investment, and difficulties in scaling up. In contrast, conventional PBRs—such as flat-panel and tubular designs—remain widely used due to their operational simplicity, predictable performance, and lower capital costs [89,90]. Studies have shown that these systems are effective for both indoor and outdoor cultivation and are well-established for producing various microalgal products [91,92]. Despite limitations such as susceptibility to contamination and energy input for mixing or temperature control, conventional PBRs are more mature in terms of commercial deployment and have demonstrated consistent productivity over long-term operations [93]. Therefore, while PV-powered systems hold promise for improving the sustainability of algal cultivation, their adoption requires further development to address practical and economic challenges compared to the reliability of traditional systems. The summary of PBR-PV integration is presented in Table 9.

5.4. Potential of algae-PV cultivation (environment, economy, and society)

5.4.1. Environment

Tables 8 and 9 present the open pond-PV and PBR-PV, respectively. From Table 8, the environmental impacts, such as land use and raw material (water) consumption, were found to have a positive direction [23]. Lesser water requirement is also observed in Reza & Parlevliet [85]. Coupling PV systems with algae ponds supports agrivoltaic applications, allowing dual use of land for biomass and energy generation. This co-location not only increases land-use efficiency but also offers microclimatic benefits—such as shading that reduces water loss and temperature stress. From Table 9, similar to the aforementioned phenomenon, the co-generation of algal biomass and electricity has resulted in lower operation costs and other added benefits, such as lesser GHG emissions and reduced climate change. In addition, a 75 % overall environmental impact reduction was found from the PBR-PV [87]. More diverse environmental benefits are observed from open pond-PV than PBR-PV, e.g., reduced pond water due to evaporation in open pond-PV system, reduced land use, and improved biomass productivity. In terms of PBR-PV, the observed benefits are primarily from the cost reduction from the electricity consumption of the PBR operation. Wastewater treatment using microalgae via photolysis also has the potential to enhance the efficiency of pollutant degradation while leveraging renewable energy sources [95–98], especially with the optimization in the Doped-TiO_2 Photocatalysts as studied by [99].

The environmental analysis can also be obtained from the life cycle analysis (LCA), which comprises four main steps: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation, is an assessment of a product's life cycle [100]. The environmental impact, cost analysis, and energy flow can be performed in LCA software via the life cycle of carbon dioxide ($LCCO_2$), life cycle costing (LCC), and life cycle energy analysis (LCEA).

Morales et al. [29] performed LCA on open pond-PV and reported that to meet the criteria of environment and energy, 20 % of PV coverture was chosen at the optimal value. From the economic perspective, a lower percentage of coverture is more desirable and vice versa for the environmental aspect. PV integration with open ponds was found to trigger a synergetic effect, and using greener electricity sources has resulted in reduced climate change impacts. PV installation at a rate as low as 10 % has demonstrated significant improvements in the environmental footprint. Further optimization of the system is potentially yielding more enhanced environmental parameters, such as ozone depletion (OD), natural land transformation (NLT), water depletion (WD), and fossil depletion (FD). Similarly, a comprehensive LCA by Gurreri et al. [101] on an industrial-scale PBR facility highlighted that electricity consumption, primarily for agitation and thermoregulation, is a major contributor to environmental impacts. This hybrid system also enhances circular economy practices by utilizing waste CO_2 and nutrients while producing bioenergy and oxygen. This integration not only contributes to carbon mitigation but also supports wastewater treatment and nutrient recycling [100].

5.4.2. Economy

From an economic point of view, the co-generation of electricity and algal biomass is economically promising for more cost-effective and sustainable algal cultivation. Hence, cheaper and more efficient bioenergy, alongside other algal-derived product production, is achievable. Although PV installation requires a high initial investment, Barbera et al. (2017) reported a faster return on investment (ROI) of the

Table 9
Microalgae PBR-PV integration from the literature.

PV type	Algae species	Findings	Limitations	References
Polysrystalline silicon PV	Not specified	• Reduced electricity demand from conventional source. • Integration with anaerobic digestion and aerobic decomposition resulted in overall environmental impact and total investment reduced by 75 % and 84 %, respectively.	• Not available at commercial scale. • High capital cost of PV installation.	[87]
Dye-sensitized cell PV	*Scenedesmus obliquus*	• Improved light energy utilization. • Enhanced microalgal production efficiency.	• Reduced biomass productivity when light is limited.	[81]
Semi-transparent dye sensitized	*Scenedesmus obliquus* and *Nannochloropsis salina*	• Photoinhibition reduction and enhanced biomass productivity during high irradiances. • Productivity similar to without PV during night time. • Promising method of improving light energy consumption and microalgal production efficiency.	• Verification of temperature variation effect on the certain wavelengths absorption and reflection of part of the (infrared) IR range is required. • PV cover reduced biomass productivity during limiting light.	[22]
Mono-crystalline	*Nannochloropsis oculata*	• Standalone system achieved.	• Growth control is essential for higher lipid content. • Simulation study required for system optimization.	[94]
Semi-transparent	*Scenedesmus obliquus*	• 73 % greater net energy ratio. • Co-production of lipid and protein. • Viable and sustainable biomass production technology.	Not specified	[88]

standalone PV-installed system compared to those without PV. In addition to energy savings, PV integration can reduce land-related expenses. Shahnazari et al. [23] reported that reduced land area requirements lower the cost of site preparation, rental, or purchase, and long-term maintenance. In addition, Li et al. [19] found higher cell density in the microalgal population with high protein and EPA (eicosapentaenoic acid) contents. The culture cost was also observed to be significantly lower than traditional culture. This indicates a possible synergy between energy optimization and high-value biomass production.

Photobioreactors (PBRs), while offering controlled environments for high-quality biomass production, are known for their relatively high energy consumption due to continuous mixing, temperature regulation, and gas exchange. Literature reports that closed PBRs may consume between 1.5 to 8.0 kWh/m^3 of culture volume per day, depending on system design and operational parameters [102,101]. This substantial energy demand contributes significantly to the overall cost of cultivation and poses a challenge for economic viability.

In this context, PV integration becomes highly relevant. By offsetting grid electricity usage, PV systems can lower operating expenses and reduce the carbon footprint of PBR operations. Susilo et al. [94] demonstrated that with proper system design and energy management, PBR-PV setups could operate as standalone units. Although the capital cost is initially higher, the premium value of lipids and proteins produced in PBRs can help justify the investment. Therefore, energy cost reduction remains a key economic benefit, helping to overcome one of the main barriers to PBR commercialization. Solar-powered microalgae cultivation aligns with circular economy principles by utilizing CO_2 emissions, wastewater, and nutrient-rich effluents as inputs, thereby closing material loops [100]. This makes the system not only an energy generator but also an effective tool in waste remediation and resource recovery. This dual function as both a biomass production platform and a tool for environmental remediation further supports the system's economic and ecological value. For example, Bárbara Vázquez-Romero et al. [103] highlighted that year-round production and improved harvesting strategies can significantly reduce costs. Similarly, Schade and Meier [36] demonstrated that tubular PBRs, if carefully designed and managed, could achieve competitive production costs under real environmental conditions.

In summary, the integration of PV systems into microalgae cultivation offers multiple economic advantages, including lower operational costs, better land use, and the potential for high-value biomass production. However, further research into system scalability, cost modelling, and process optimization is still needed to realize full commercial potential.

5.4.3. Society

From a societal standpoint, local bioenergy production can reduce the public energy burden, improve health via lower air pollution, and enhance energy autonomy. With the right policy incentives—such as carbon credits, feed-in tariffs, or green bonds—these systems become even more viable, encouraging their deployment in both developed and developing regions [36].

6. Conclusion

The review has presented the current progress in traditional microalgal cultivation systems, including open ponds and photobioreactors (PBRs), as well as their integration into hybrid configurations and photovoltaic (PV)-powered systems. Hybrid open pond–PBR and indoor–outdoor combinations demonstrate improvements in energy efficiency, biomass productivity, and cost-effectiveness through the utilization of simpler construction materials and the ability to maximize sunlight exposure. Meanwhile, open pond–PV systems show promise in reducing operational costs and water evaporation losses, with some studies reporting faster return on investment compared to non-PV setups. Despite seasonal fluctuations, these systems offer enhanced sustainability by partially replacing grid electricity and enabling simultaneous algal growth and renewable energy generation. PBR–PV systems, though more capital-intensive, offer a stable and controlled environment that supports the co-production of high-value biocompounds such as lipids and proteins.

Nevertheless, several challenges remain unresolved and warrant further investigation. One critical area is the optimization of PV module placement and surface coverage to balance light penetration and shading effects, thereby reducing photoinhibition while promoting lipid accumulation. Scalability studies are urgently needed to transition lab-scale or pilot systems into full-scale industrial applications, especially in variable outdoor environments. In addition, life cycle assessments and techno-economic analyses must be integrated into future research to evaluate long-term viability, environmental impact, and cost performance under real-world operating conditions. The development of advanced monitoring and control systems, including dynamic temperature regulation, artificial lighting, and automated nutrient delivery, could further improve productivity and system resilience in fluctuating climates. Altogether, these strategies offer a roadmap for translating PV-integrated algal cultivation into a viable and scalable technology, supporting sustainable bioresource production and contributing to global renewable energy goals.

CRediT authorship contribution statement

M.S.N. Atikah: Writing – original draft, Conceptualization, Methodology. **Razif Harun:** Writing – review & editing, Supervision. **R.A. Ilyas:** Writing – review & editing. **Mohd Nor Faiz Norrrahim:** Writing – review & editing. **Victor Feizal Knight:** Writing – review & editing.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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