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Solar technology–closed loop synergy facilitates low-carbon circular bioeconomy in microalgal wastewater treatment

Praveen Kuppan[1], Abinandan Sudharsanam[1,2], Kadiyala Venkateswarlu[3] and Mallavarapu Megharaj[1,2]✉

The circular bioeconomy framework addresses the global transition toward resource-efficient and low-carbon economies. The use of microalgae in sustainable circular bioeconomy largely suffers from energy consumption and underutilization of residual biomass, leading to greenhouse gas (GHG) emissions. This analysis-based perspective reveals that closed loop microalgal wastewater systems reduce GHG emissions by >50% and enhance valorization of residual biomass for value-added products compared to open loop approach. Integrating solar technologies in closed loop system further reduces GHG emissions by 99% and aligns with 11 UN sustainable development goals, making it a suitable model for a zero-waste and low-carbon circular bioeconomy.

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INTRODUCTION

Anthropogenic CO_2 emissions account for about 84% of global CO_2 emissions, mostly contributed from the energy systems and industrial activities because of the linear economy (think-make-waste) approach[1]. A circular economy aims to replace the linear concept of take–make–use–dispose paradigm of production and consumption with a circular model in which resources may be reused or (bio)degraded and re-integrated back into the system by reducing negative externalities and fostering restoration and regeneration[2–4]. As a general concept, the term "bioeconomy" refers to the use of biological resources, products, and processes in lieu of fossil fuels for the creation of services and commodities[3–5]. Europe's policy objectives together with the research and innovation initiatives converged the models of bioeconomy and circular economy to achieve climate-neutral growth[6]. Thus, the term "circular bioeconomy" became more prominent as it appeared in policy and scientific literature after the release of the EU Circular Economy Action Plan in 2015[7]. From a biotechnological viewpoint, circular bioeconomy is currently a viable sustainable development strategy to obtain value-added products from renewable biological resources (e.g., wastewater and waste) and protect the long-term worth of resources using enhanced conversion biotechnologies[8]. Microalgae produce biomass by utilizing solar energy that can be valorized into useful products[9]. However, when compared with other conventional wastewater treatment technologies, cultivation of microalgae in wastewaters and subsequent biomass production have been widely considered in circular bioeconomy approach[10–14].

Open loop and closed loop approaches refer to two types of systems or processes that involve the use of resources (Fig. 1). Open loop or linear approach uses the resources only once and discards them without reusing or recycling[15]. In contrast, closed loop or circular approach reuses the resources within the system, thus promoting a circular use and reducing the generation of waste[16]. In a microalgal biorefinery process, the biomass value is limited to its lowest feasible flows of matter and energy for producing bioproducts[11]. After the desired output, the remaining biomass residue ends up as a waste in open loop approach. Therefore, to minimize the generation of waste and to exploit the resource efficiency of the product, it is important to decouple the risk of following a linear (open loop) valorization of algal biomass because the closed loop approach helps to reduce this risk through maximizing the biomass utilization. During the entire closed loop strategy, applications of biomass are made more sustainable by the regeneration of multiple bioproducts instead of its disposal at the end[16]. Thus, the closed loop process not only minimizes the negative ecological impact but also creates a positive thrust on economic and social systems[9,17,18].

Several reports claimed biomass valorization using open loop approach as a sustainable model for microalgal system in producing a single bio-product at the end of the biomass lifecycle such as biogas[19], bio-oil and biodiesel[20,21], and biofertilizer[22–24]. Another significant issue in the open loop approach that may forbid the advancement of sustainable microalgal technologies is the downcycling process, which reduces the value of the material thus making it difficult to reuse in the flow again[25,26]. This clearly implies that most of the researchers follow open loop approach and pay very little attention to the residual bio-based products in microalgal systems, eventually ignoring the perspective of "sustainable microalgal technology". Despite the direct environmental benefits and technological viability of microalgae-based energy products, the entire process in the open loop approach is expected to consume high energy[27–35] compared to the closed loop strategy (Fig. 2). Based on compilation of energy consumption data available in the literature for microalgal systems, we found that the total share of energy in the open loop approach was significant and varied with factors such as volumetric productivity, harvesting efficiency and generation of several bioproducts (Supplementary Tables 1–3). Besides the energy demand and land requirement for biomass generation, recent models indicate that bioenergy derived from biomass is crucial for replacing fossil fuel sources[36,37]. Luderer et al.[38] emphasized that insufficient biomass availability will increase the resilience of fossil fuel dependence and suggested the use of technological innovation in non-renewable biomass technology as it continues to reduce costs, making it the principal enabler of decoupling electricity prices from rising carbon prices.

[1]Global Centre for Environmental Remediation (GCER), College of Engineering Science and Environment, ATC Building, The University of Newcastle, Callaghan, NSW 2308, Australia. [2]Cooperative Research Centre for Contamination Assessment and Remediation of Environment (CRC CARE), The University of Newcastle, ATC Building, Callaghan, NSW 2308, Australia. [3]Formerly Department of Microbiology, Sri Krishnadevaraya University, Anantapuramu 515003, India. ✉email: megh.mallavarapu@newcastle.edu.au

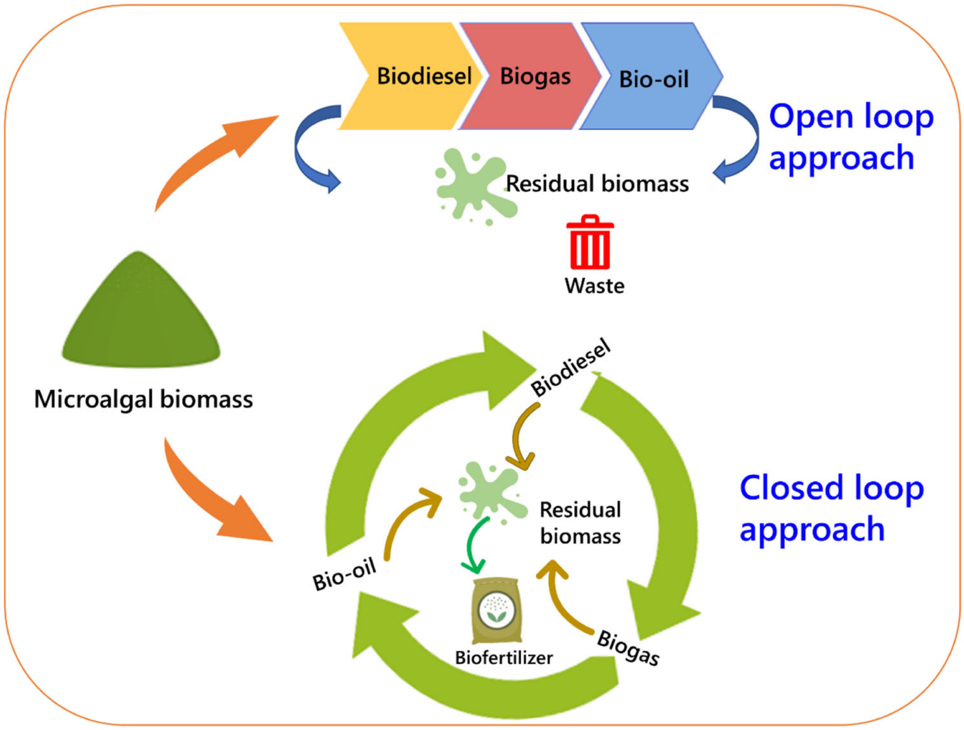

Fig. 1 Open loop and closed loop approaches in microalgal technology for biomass valorization.

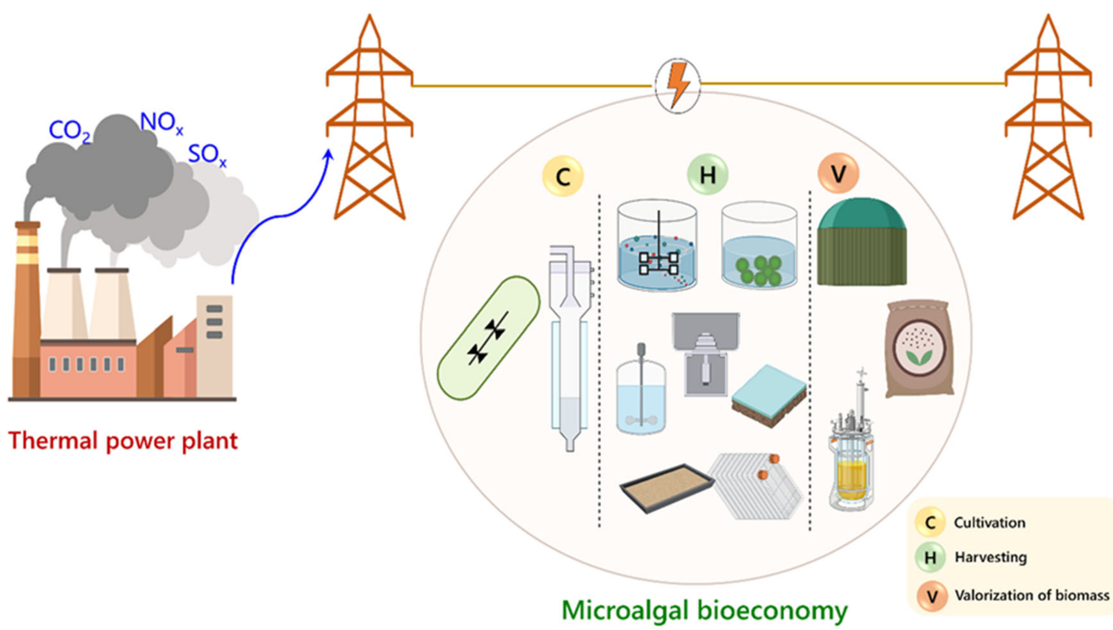

Fig. 2 Use of fossil fuel and its negative impact, in terms of greenhouse gas (GHG) emissions, on microalgal bioeconomy.

In general, the perception of integrating renewable technology in any system is widely regarded as feasible for lower operating costs, greater competitiveness than conventional energy sources[38–41]. Furthermore, the technical potential of solar energy not only outpaces bioenergy but also rapidly gains traction in both established and emerging markets developments[37]. This clearly implies that solar energy is only marginally represented in energy systems so far, thus providing a compelling reason to propose a synergy of solar energy in the closed microalgal system as it plays a crucial role in low-carbon economy. Here, we systematically analyzed the key components such as energy consumption, residual biomass valorization, and GHG emissions in open loop and closed loop approaches for microalgal systems and demonstrated the eco-effectiveness and sustainability of the latter in wastewater treatment. Also, the results on carbon emission analysis indicated that the transition toward closed loop approach is more appropriate for low-carbon circular bioeconomy in microalgal technology. To enhance the sustainability of solar energy across a diverse suite of recipient environments, Hernandez et al.[42] recently proposed a new concept of synergy framework for mutually beneficial relationships between technological and ecological systems. In the present analysis-based perspective, we propose the synergy of solar technologies in closed

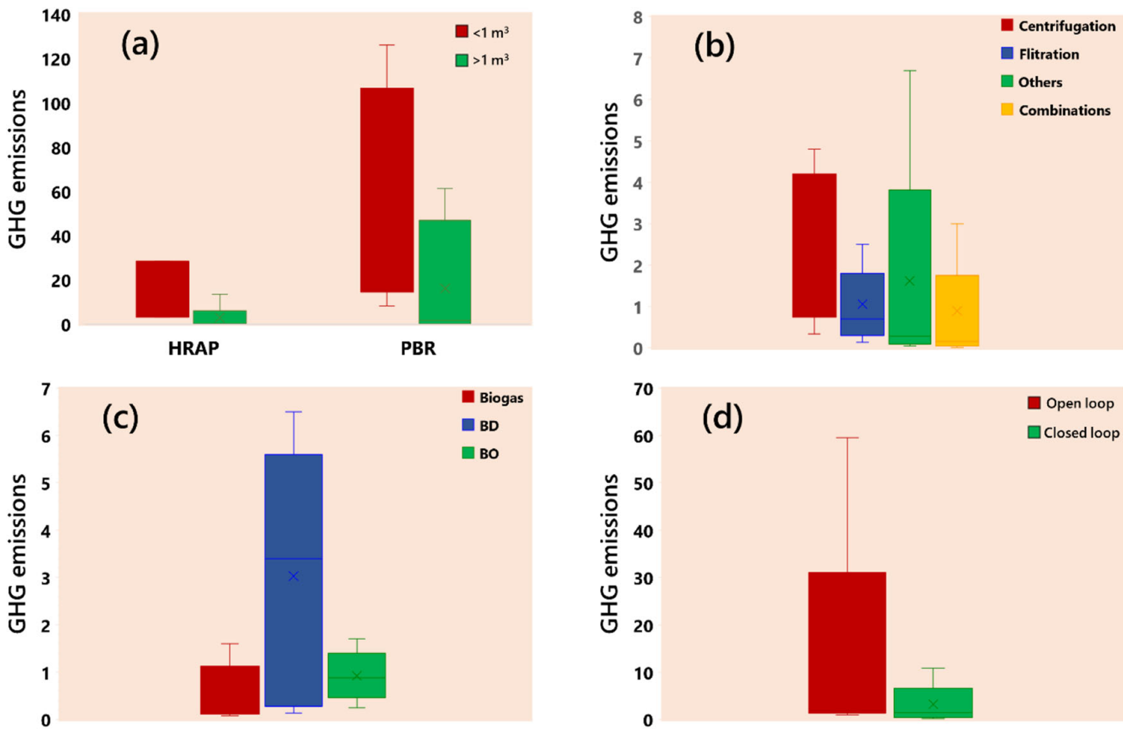

Fig. 3 GHG emissions (kg CO_{2eq}. kg^{-1} biomass) from microalgal technology. **a** Cultivation systems, **b** Harvesting, **c** Biomass valorization (BD, biodiesel; BO, bio-oil), and **d** Open loop and closed loop approaches.

loop approach for biomass production and its valorization and validated its sustainability in low-carbon circular bioeconomy by aligning with the UN SDGs.

CLOSED LOOP APPROACH: AN ECO-EFFECTIVE STRATEGY IN MICROALGAL SYSTEM

Closed loop approach is eco-effective due to the generation of multiple bioproducts from the microalgal biomass, which would be otherwise wasted in an open loop process[2]. While supporting the closed loop strategy, Hemalatha et al.[43] showed that linking several bioprocesses in closed biorefinery approach will help maximizing microalgal biomass recovery, making it an economically viable system. Similarly, Mohan et al.[11] observed the potential of microalgal biomass valorization in integration modes since the "closed circular loop" of microalgal biorefinery enhances the economic feasibility and environmental sustainability. While considering microalgae as a renewable source of third-generation biofuel in yielding multiple products through biomass valorization, Debanath et al.[44] recently recommended the technoeconomic feasibility of the closed loop concept in circular bioeconomy. Thus, the use of such tools as life cycle assessments (LCA) and technoeconomic analysis (TEA) is crucial in ensuring economic and environmental impacts in microalgae-based bioeconomy approaches. Lopes et al.[45] conducted a techno-life cycle analysis and showed that biomethane purification from the closed loop algal biorefinery process resulted in a 2% increase in electricity consumption with a neutral energy balance. Also, Quinn et al.[46] reported that well to wheel analysis for upgrading biofuel can add up to 72 g CO_2 MJ^{-1}. On the other hand, DeRose et al.[47] demonstrated that total GHG emissions associated with the thermochemical pathway for algal biofuels based on well to wheel were lower than those for both soybean and conventional diesel emissions. Similarly, Hydrothermal Liquefaction (HTL) process for algal biomass was found to be sensitive to several parameters affecting its economics. Among the parameters, the cost of algal feedstocks, bio-oil conversion rate, and internal rate of return were identified as significant factors[48]. However, the upgradation process needs to be changed to obtain the targeted biofuel from algal biomass. Based on well to wheel analysis, Dutta et al.[49] showed that the required upgradation resulted in >2000% increase in bio-oil compared to biodiesel. All these studies highlight that energy involved in the process plays a major role in closed loop algal biofinery processes[50]. Interestingly, GHG emissions also depend on the nature and quantities of co-product generated from microalgal biomass[15]. Likewise, Karan et al.[51] showed that HTL fuel has a higher energy and GHG impact compared to other co-products in a microalgal closed loop biorefinery due to the complexity of the process. Since energy is essential for enhancing sustainability in microalgal closed loop processes, Gerrior et al.[52] suggested that reduced energy use for the yield of appropriate saleable co-products decreases the investment costs. Net energy ratio (NER) is critical in demonstrating the energy demand of microalgae sustainable and commercially viable products. The NER values estimated for biodiesel, HTL, and pyrolysis were 0.93, 2.40, and 2.90, respectively[53,54]. Overall, it is evident that energy consumption is a major limitation in the algal-based closed loop process during the operational phase and is critical to the environmental impact and capital costs[55].

CARBON EMISSION ANALYSIS: A KEY CHARACTERISTIC OF SUSTAINABILITY IN MICROALGAL TECHNOLOGY

Energy is the primary source of carbon emissions from every sector of the global economy. Considering only the energy related to indirect emissions of GHG, we assumed that the total energy consumption for the microalgal biomass production and subsequent valorization was through electricity imported from fossil fuel-fired power plants. Hence, to understand the environmental implications through energy utilization standpoint, we performed the carbon emission analysis from several unit operations such as cultivation, harvesting and biomass valorization both in open and closed loop approaches based on the energy consumption per kg of biomass (Fig. 3). In the present analysis, the overall carbon emissions were determined using the GHG equivalencies calculator of the United States Environmental Protection Agency (US EPA) available at www.epa.gov and expressed the GHG value as kg CO_{2eq}. Assuming that the average emission factor is 4.03×10^{-4} metric tons CO_{2eq}, as suggested by the US EPA, we calculated the energy consumption in terms of kWh kg^{-1} biomass. While the conversion factor and location of each study in the literature can vary, we assumed that the national electricity network of the corresponding studies was analogous to the US energy mix for estimating comprehensive GHG value. This estimation provides a significant value in conceptualizing the mass of carbon emissions. For example, to generate 1.0 kg of biomass, high-rate algal pond (HRAP) with a volume capacity of <1.0 m^3 exhibited a five-fold increase in GHG emissions compared to the scaled-up volume of >1.0 m^3. Similarly, the use of <1.0 m^3 photobioreactor (PBR) volume to generate 1.0 kg biomass, the GHG emission was three-fold higher compared to the reactor volume of >1.0 m^3. Overall, HRAPs demonstrated lesser GHG emissions compared to PBRs (Supplementary Table 1). Thus, the reduction of GHG emission was 72 and 81% in HRAP for volume capacities of <1.0 m^3 and >1.0 m^3 compared to PBRs. For harvesting 1.0 kg microalgal biomass using centrifugation, filtration, and other processes such as magnetic separation and flotation, either alone or in combination, the GHG emissions were in the order: centrifugation > other processes > filtration (Fig. 3 and Supplementary Table 2). Interestingly, combination of harvesting process (preceded with gravitation settling, coagulation/flocculation) showed 14% reduction in GHG emissions compared to filtration. Similarly, in biomass valorization to obtain value-added products, particularly biodiesel, following the transesterification process, there was a three-fold increase in emission as compared to the production of bio-oil and biogas from hydrothermal liquefaction and anaerobic digestion (Fig. 3 and Supplementary Table 3).

CAN CLOSED LOOP APPROACH ADDRESS THE PITFALLS OF OPEN LOOP STRATEGY?

The use of wastewater as a growth medium in microalgal systems can provide added value to biomass generation, thereby enhancing sustainability[55]. The algal-based systems can also influence the nutrient removal capacity in wastewaters depending on the pre-treatment (anaerobic or aerobic) used. The use of anaerobically pretreated effluent of municipal wastewater in algae-based systems can remove ~40–60% of carbon and nitrogen load with only 10–15% removal of phosphate[56–58]. But in aerobic-pretreated systems, algae can remove over 60% of pollutants with a significant (>70%) phosphate removal. However, the pollutant removal efficiency varies with the conditions and the source of wastewater used in the treatment systems. Nonetheless, the quality criteria set for the discharge of treated water need to be followed irrespective of the pre-treatment process[45,57–60]. In addition, Bauer et al.[61] recommended legislation to ensure the quality of bioproducts derived from microalgae in the circular economy. Our present analysis of the available scientific data reveals that GHG emissions (kg CO_{2eq}.) in the open loop approach are five-fold higher than in the closed loop approach indicating the need for generating multiple products from algal biomass (Supplementary Table 4). Furthermore, our analysis suggests that GHG emissions associated with closed and open loop approaches vary depending on the targeted bioproducts. The range in GHG emissions (kg CO_{2eq}.) for the production of biogas, bio-oil, and biodiesel in the open loop process was 1.20–44.60, 7.50–59.50, and 1–70.50, respectively. In contrast, the yield range was significantly lower in the closed loop process for biogas and biofertilizer (0.46–8.90), bio-oil and biogas (6.20–283), and biodiesel and feed (0.17). Although the overall CO_2 emission was lower in the closed loop system as compared to the open loop process, the maximum emission (283 kg CO_{2eq}.) for the yield of bio-oil and biogas was due to higher energy requirement in the anaerobic pre-treatment process. Although anaerobic digestate is a rich source of organic matter and micronutrients that can be used as soil amendment[16,62], effective measures to control harmful chemicals, especially heavy metal ions and antibiotics, are crucial to ensure the safety of microalgal biomass for its use in aquaculture and agriculture[63]. Proper heat treatment to prevent pathogen contamination during bioenergy recovery and recycling liquid from biogas can comply with European biogas methane regulations[64]. The selection of co-products and managing energy consumption in a closed loop are therefore essential to reduce GHG emissions and promote sustainability.

SOLAR TECHNOLOGIES FOR ENHANCING SUSTAINABILITY OF MICROALGAL BIOMASS PRODUCTION

One of the many opportunities for reducing the energy consumption, carbon footprint and cost associated with the operation for microalgal cultivation and biomass production is to adopt an approach for renewable sources of energy. Solar irradiance for desirable microalgal growth can be distinguished into direct photosynthetically active radiation (PAR) and indirect PAR (solar thermal, photovoltaic (PV), luminescent solar concentrators (LSCs), while direct PAR from sunlight is utilized in general open pond and closed PBR[65–69]. Light penetration and its distribution in PBR are the crucial factor since the light intensity decreases as it moves away from the closer proximity[70–72] and forms larger dark areas inside the PBR making the microalgal systems unproductive[73]. The indirect PAR application iterates the use of solar technologies such as solar thermal or PVs or LSCs essentially for optimal microalgal cultivation even during night[70–73]. Several other reports have discussed the option of converting blue or green to red spectrum for enhancing microalgal growth using luminescent materials[74–79]. However, these approaches using luminescent materials have limitations such as low optical efficiency, lack of general effectiveness, and less effective biomass generation. Table 1 summarizes the solar technologies used in microalgal cultivation together with their advantages and limitations.

Solar thermal technologies use water or air to convert solar radiation into thermal energy, while PV solar technologies convert sunlight into electricity. Solar PV is a promising and popular renewable energy technology with an efficiency of 10–23%. Conventional modules (silicon monocrystalline and polycrystalline cells) and semi-transparent modules (organic solar, dye-sensitized cells or other advanced technologies). Due to abundant solar radiation and cost benefits, microalgal systems use solar thermal. Several reports show the use of solar thermal technologies such as Fresnel lens, solar collectors, mirrors, and parabolic trough[80–84] and PV[85–88] in microalgal systems for biomass production and valorization. A detailed overview on solar PAR and non-PAR applications in microalgal systems is presented in Fig. 4. Recently, integration of solar PV with LSC has been employed to compensate for the loss by redirecting non-use spectrum into solar cells for electricity generation by placing a solar panel above a microalgal cultivation[86,89] in greenhouses where PV modules increased photoconversion efficiency of sunlight to electricity, covering the energy required for the whole process and allowing overproduction for economic benefit.

SOLAR CLOSED LOOP APPROACH—A ZERO-WASTE LOW-CARBON BIOECONOMY MODEL

Given their ability to adapt and undergo closed loop sequential extractions, microalgal biomass can be effectively used for zero-waste low-carbon bioeconomy models. This closed loop biomass approach increases interest in generating energy and reducing carbon footprints for low-carbon bioeconomy. Developing an

Table 1. Advantages and limitations of solar technologies in microalgal cultivation systems.

Technology	Energy requirement (kg^{-1} biomass)	Land requirement (kg^{-1} biomass)	Advantages	Limitations	Ref.
Green solar collector (GSC)	NA	NA	Constructed with durable plastics and is light in weight. The reactor can thus be easily placed on horizontal rooftops and can be an alternative to conventional thermal or photovoltaic (PV) solar collectors.	The production costs of the GSC are expected to be higher than those of conventional PBR.	80
Two-stage solar photobioreactor (PBR)	NA	266 m^2	Relatively low biomass density (0.20 g l^{-1}), more than 60% of light is absorbed in just a few mm of the photic zone in the suspension.	About 25% of radiant energy is lost by reflection or absorption by the tube wall.	81
Front-facing photovoltaic (PV) cell-Luminescent solar concentrator (LSC)	NA	NA	Paddlewheels, fans, sensors, and other electronic devices for both control and LSC greenhouse operations are powered by the PV cells during the algal growth trials, demonstrating the capacity of these PV panels to produce enough electricity to power greenhouse operations.	Photosynthetic efficiency is higher for the solar spectrum treatment as compared to the LSC treatment.	85
PV-PBR	NA	30 m^2	Increase the overall photoconversion efficiency of the system by producing directly available electrical energy together with microalgal biomass.	At low light intensities, the presence of PV panel causes a small loss in biomass concentration.	95
Dual-energy generator integrating PVs	NA	45 m^2	Achieves 85% of the reference biomass productivity with only 55% of the photon numbers, additionally generating high voltage electricity from the remaining high energy photons.	PV absorbs only IR photons over 700 nm and limits the maximum power conversion efficiency.	96
Standalone PV-powered PBR	2.90 kWh	50 m^2	The net energy ratio is greater (73%) compared to the conventional PBR.	Incorporation of spectral selection and integration with transparent PV should play a significant role in future scenarios for the scaling up of grid-independent production of biomass, bioproducts and renewable electricity from a single algal plant installed.	97
PV-assisted greenhouse	2.80 kWh	43 m^2	Reduces photosaturation and photoinhibition effects. Market price of biomass decreases by the presence of PV.	Decrease in biomass production in the winter season when energy from sunlight is limited.	89
Novel PBR supported with mirror	NA	60 m^2	Light-to-biomass conversion efficiency is more than in conventional PBRs, as cell doubling rate and biomass productivity increases by >55%.	Higher frequencies than 100 Hz, results in photosynthetic activity resembling the continuous light, due to high succession of photon flux. Requires optimal light.	82
Integrated PBR covered by a novel semi-transparent dye-sensitized PV module	NA	37 m^2	The PV module absorbs only a range of wavelengths while part of the energy is transmitted through the PBR walls, producing directly available electrical energy together with microalgal biomass.	Since light is limiting, the PV cover decreases biomass productivity. Beneficial effect of PV under high irradiances, with reduction in photoinhibition and increase in biomass productivity.	98

NA – Not available

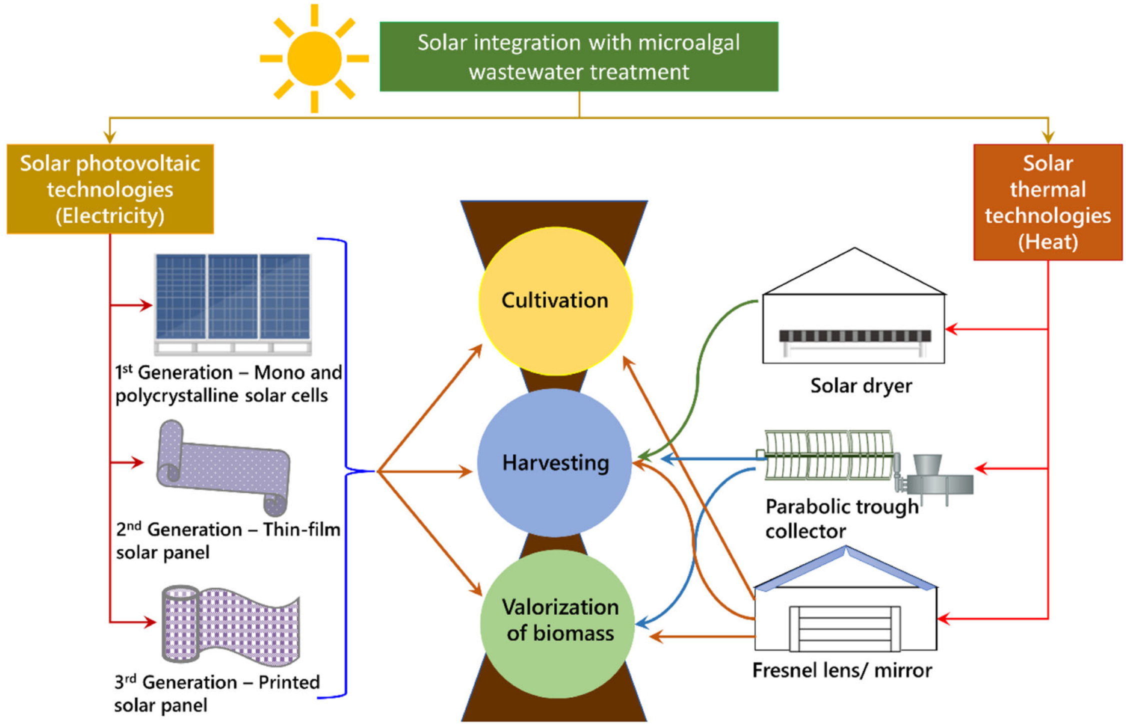

Fig. 4 Integration of solar technologies (photovoltaic (PV) and thermal) in microalgal wastewater treatment for cultivation, harvesting and biomass valorization.

algal bioeconomy on the back of fossil fuels is not sustainable. Even with carbon capture and storage (CCS), algal biomass produced with fossil fuels contributes to climate change by emitting GHGs. Therefore, it is important to measure and compare carbon emissions from the entire process. Our analysis of the published data on conventional energy in the closed loop approach of biomass valorization for bio-oil and fertilizer revealed a great potential for GHG emissions[90]. For biogas and fertilizer, 1.0 kg algal biomass emits 0.17–5.0 kg CO_2[91]. Therefore, an effort to present a comparison of GHG emission between conventional energy and solar PV-powered microalgal wastewater treatment and biomass valorization was made in the first scenario for circular bioeconomy products. To avoid the error and difference in the systems configuration and infrastructure, GHG emission was considered for 1.0 kg of algal biomass production and valorization. We found emission reduction of over 99% while switching to solar PV for both the cases of bio-oil and fertilizer and biogas and compost whereas it was around 94% reduction in the case of producing biogas and fertilizer. We further explored the solar thermal technology as a replacement for the drying process to complement the solar PV system in the above case and found a similar trend in GHG emission reduction which was ˃99% for bio-oil and fertilizer, and biogas and compost in closed loop approach. However, the GHG emission reduction was around 97% for biogas and fertilizer as the value-added products. This shows that solar energy option can provide significant advantages, in terms of reduction in GHG emission, in comparison with fossil fuel energy even when embodied energy from solar technologies are considered. Although the feasibility of rapid deploying renewable energy sources to upstream and downstream processes of microalgae is unclear, exploring solar energy can be a better option as it is more convenient for installation and maintenance. In all, to demonstrate the sustainability of the low-carbon economy in microalgal wastewater treatment, here we proposed a circular bioeconomy model by integrating renewable solar energy with biomass production and its valorization for value-added products such as bio-oil, biogas and biofertilizer (Fig. 5).

This system encompasses solar PV cells as the source of energy and an affordable solar thermal dryer, a substitute for conventional ovens, in the dewatering process. Similarly, for valorization of algal feedstock, solar parabolic trough collector-based hydrothermal liquefaction process is integrated for the extraction of the oil[92] followed by an anaerobic digestion process for producing biogas wherein digestate can be used as fertilizer. Compared with the conventional data available in the literature, replacing fossil energy with combination of PV and thermal results in an estimated total GHG emission of 0.04 kg CO_2 kg^{-1} microalgal biomass. Therefore, supporting an algal circular bioeconomy by renewable energy resources can offer immense potential in minimizing the environmental impacts.

CAN SOLAR CLOSED LOOP APPROACH MEET GLOBAL SUSTAINABILITY TARGETS?

Sustainability in circular bioeconomy model for wastewater treatment is possible by bringing in efficient strategic metrics. Following an interaction between the present model with the concept of water-energy-food (WEF) security nexus, we proposed here a sustainable model that can significantly contribute to the issues of water crisis, and energy and food production (Fig. 6). Since microalgal biotechnology integrates and connects several SDGs[93], the proposed model also supports tangibly and intangibly the following SDGs: sustainable economic growth (SDG 8), innovation and infrastructure (SDG 9), sustainable communities (SDG 11), improved resource efficiency (SDG 12), climate action (SDG 13), life below water (SDG 14), life on land (SDG 15), and partnership in goals (SDG 17). Moreover, the imperceptible benefit of WEF nexus alignment can be realized through delivering treated water, bioenergy, solar energy and biofertilizer from microalgal technology and help expanding SDGs horizon like zero hunger (SDG 2), treated water and sanitation (SDG 6), affordable and clean energy (SDG 7), and climate action (SDG 13). Broadly, sectoral issues like water, energy and food cannot be considered in isolation and nexus-based approaches are promoted and

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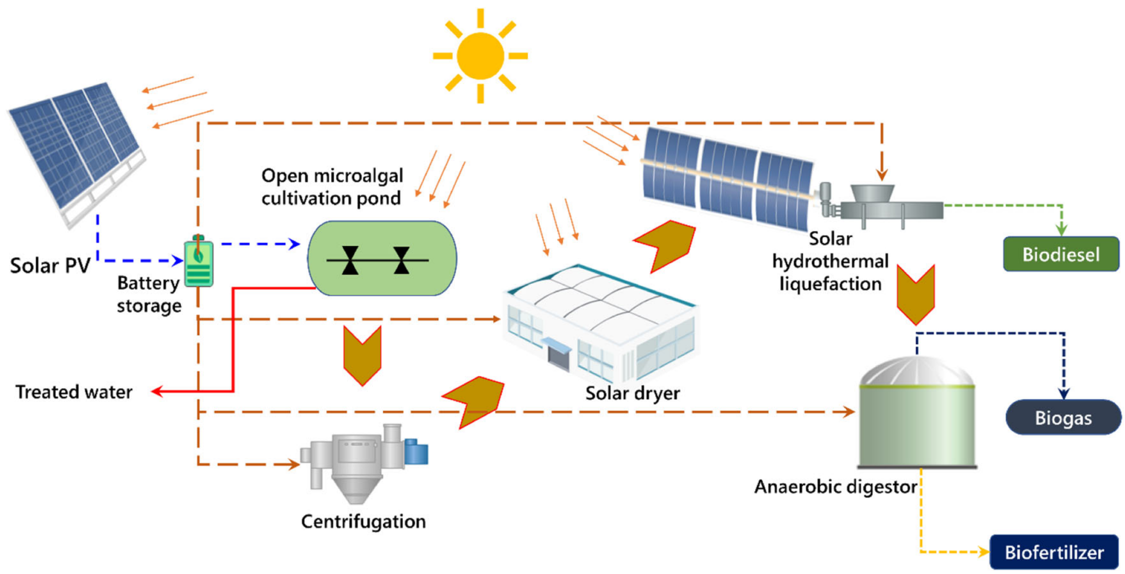

Fig. 5 Proposed model for solar technology-integrated microalgae-based circular bioeconomy in wastewater treatment.

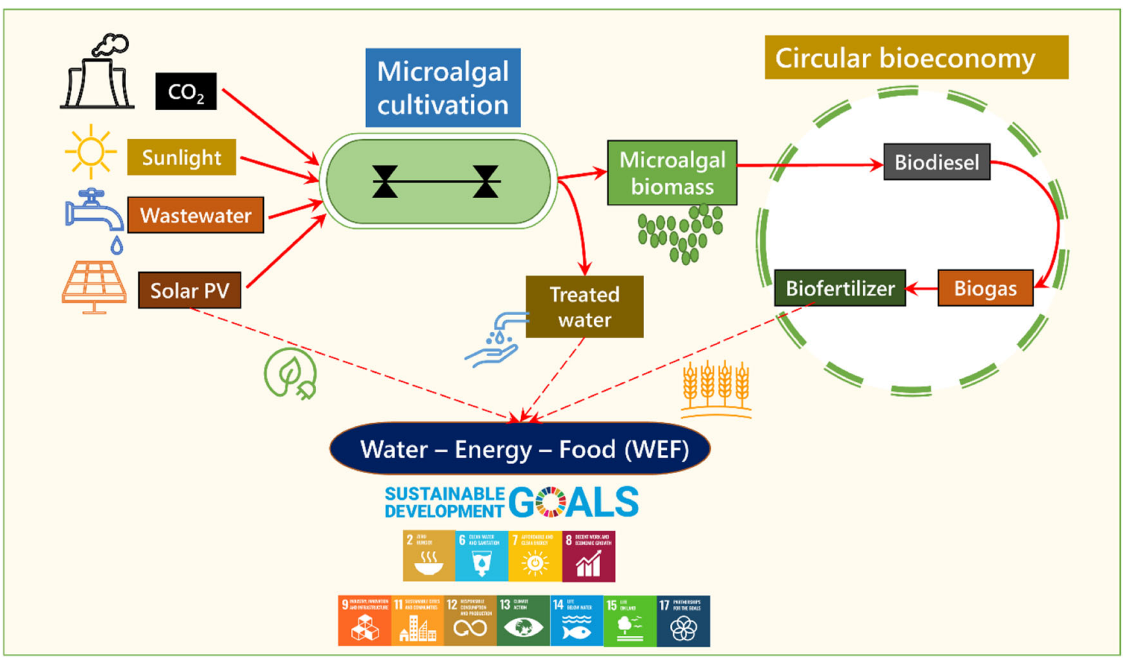

Fig. 6 Integration of the proposed model for microalgal circular bioeconomy with water–energy–food (WEF) nexus and alignment with UN sustainable development goals (SDGs).

highlighted for effective SDGs[94]. However, to guarantee a successful bioeconomy, it is necessary to understand the intersection of interaction between the agriculture, energy, industrial and transport sectors. Thus, an eco-innovative, economical, and sustainable closed loop biomass valorization is necessary to reuse the algal residue that will pave for sustainable circular bioeconomy.

To sumup, measuring the circularity of products and services, in a shift toward the circular economy, is essential while designing policies and strategies. Moreover, prioritizing sustainable evidence-based outcomes can play a significant role. Using the readily available nutrients in the wastewater for energy production, the microalgal circular bioeconomy model can work as a key lever on the path toward decarbonization in wastewater treatment. A comparison of the energy consumption and GHG emission performance at varying levels of microalgal cultivation, harvesting and biomass valorization revealed that the energy requirement for microalgal wastewater treatment could contribute a significant share of indirect emissions. On average, the range in GHG emission of the open loop approach was 5–30 kg CO_2 kg^{-1} of biomass, whereas the corresponding values in the closed loop approach were <10 kg CO_2 kg^{-1} of biomass. With the abundant source of solar energy available across the globe, we proposed the integration of solar energy with the closed loop approach for microalgal wastewater treatment. Thus, solar integration into closed loop approach exhibited >99% reduction in carbon emissions, clearly supporting its self-sustainability besides adding value to the economy. While this step could bring attention to eliminating indirect emissions from microalgal wastewater treatment, biomass valorization techniques warrant greater attention to meet efficient resource recovery. As an accelerator for sustainable microalgal wastewater treatment, the proposed solar closed loop concept of downstream biomass valorization can deliver positive effects, including energy (shift to renewable energy), water (less freshwater), industry (less diesel and fertilizer production), agriculture (less energy and fertilizer use), and waste sector (less sludge and methane emissions from landfills). When managed properly, closed loop approach can be realized without compromising the resource efficacy that brings tremendous value to the wastewater treatment industry by providing unique opportunity for addressing the WEF nexus. Therefore, the concept of utilizing renewable solar energy for closing biomass material loop prevents uncontrolled waste disposal and can form a crucial step toward a low-carbon sustainable circular bioeconomy.

DATA AVAILABILITY

The data supporting the findings of this study are available within the paper and its Supplementary Information file. Further data can be requested (if need be) by contacting the corresponding author.

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AUTHOR CONTRIBUTIONS

P.K. and A.S.: conceptualization, methodology, writing original draft. P.K. and K.V.: review and editing. M.M.: conceptualization, validation, resources, supervision, review and editing, administration.

COMPETING INTERESTS

The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to Mallavarapu Megharaj.