JEE Journal of Ecological Engineering

Journal of Ecological Engineering 2022, 23(9), 309–318
https://doi.org/10.12911/22998993/150627
ISSN 2299–8993, License CC-BY 4.0

Received: 2022.05.13
Accepted: 2022.07.18
Published: 2022.08.01

Microalgae Biomass Modelling and Optimisation for Sustainable Biotechnology – A Concise Review

Adamu Yunusa Ugya[1, 2], Kamel Meguellati[1]

[1] School of Pharmacy, Jinan University, 855 Xingye Avenue East, Guangzhou, 511436, China

[2] Departments of Environmental Management, Kaduna State University, Tafawa Balewa Way, Kabala Coastain 800283, Kaduna, Nigeria

* Corresponding author's mail: kamel2021@jnu.edu.cn

ABSTRACT

The autotrophic forms of microalgae are referred to as "efficient biological factories", because they play a significant role in CO_2 removal from the atmosphere by utilizing it for the process of photosynthesis. The industrial application of microalgae biomass includes the production of cosmetics, health products, fertilisers, biofuel, feeds, and food. Microalgae biomass is also an important tool used in the treatment of wastewater. The current review is aimed at reviewing the progress and prospects of microalgae resource modelling and optimisation as a tool for sustainable biotechnology. The mechanism of biomass production by microalgae tends to vary according to whether the microalgae are autotrophic, heterotrophic, or mixotrophic organisms. In the current study, the modelling and optimisation of microalgae biomass production were discussed, as well as the modelling of CO_2 sequestration, light intensity, nutrients, and photobioreactor. The role of microalgal biomass production in attaining sustainable biotechnology has also been extensively studied. Microalgae are an emerging tool used in the phycoremediation of wastewater and reduction of high CO_2 level. The modelling and optimisation of microalgae biomass production will help to upscale the production of the microalgal based fuel and bioproducts from model scale to the money-making level.

Keywords: bioresources, wetland technology, bioremediation, biomass optimisation.

INTRODUCTION

Microalgae are group of microscopic, unicellular, photosynthetic and heterotrophic groups of organisms which are often referred to as the ancestral organisms that make up the primary producers of aquatic ecosystem (Singh et al., 2017; Ugya et al., 2021b). They play an important role in fresh and marine habitats because they are adapted and tend to grow well in both freshwater, marine water and hyper saline environment (Alvarez et al., 2021; Zafar et al., 2021). Microalgae are renewable resources that can grow as autotrophs, heterotrophs, or mixotrophs. The autotrophic forms of microalgae are referred to as an efficient biological factory because they play a significant role in CO_2 removal from the atmosphere by utilizing CO_2 for the process of photosynthesis (Dixon & Wilken, 2018; Ugya et al., 2020b). They also transform this atmospheric CO_2 into high-value bio resources, such as proteins, starch, lipids, and other biomolecules in the presence of nutrients and solar energy (Vale et al., 2020). Heterotrophic microalgae, such as cyanobacteria are considered bio fertilisers due to their role in fixing atmospheric nitrogen and solubilising immobilised phosphorus in the soil (Singh et al., 2016). Microalgae are an important biotechnological tool which has diverse industrial application including biofuels, food, feed, cosmetics, aquaculture, and pharmaceuticals (Raja et al., 2018). The studies on the use of microalgae biomass as a source of renewable energy is intensifying, because under suitable culture conditions, most microalgae species tend to accumulate up to 50–70% of lipid per dry weight which are suitable for the synthesis of biofuels (Amaro et al., 2017; Ugya et al., 2021c).

The goal of natural resource management is to sustainably utilise natural resources such as water, land, forest, fisheries, and mineral resources with more emphasis on non-renewable mineral resources due to their non-renewable characteristics (Muralikrishna & Manickam, 2017). The management of non-renewable resources is necessary due to the continuous demand and fast depletion of fossil fuels. To prevent the exhaustion of fossil fuels, it is important to search for alternative energy resources. Biofuels, either biodiesel or bioethanol, are an alternative important source of energy that can be used to replace fossil fuels (Khanna et al., 2011). This form of biofuel, termed "bioeconomic," is a lasting solution that utilizes bioresources in place of fossil resources. Bioeconomics increases environmental sustainability, limits fossil feedstocks and prevents the negative effects of fossil resources on the environment (Acién et al., 2017). The materials utilised in biofuel production include food crops, crop waste, woody parts of plants and fruits. These biomaterials are also important in the basic life routine of man. It is therefore very important to obtain alternative bioresources with minimal basic life support (Balan, 2014). Microalgae biomass utilisation can solve the problems associated with non-renewable resource sustainability due to the ability of microalgae to accumulate high starch and lipids in their biomass, making it an emerging tool for bioresource production due to its fast biomass growth (Khan et al., 2018a). Microalgae biomass is also rich in metabolites, such as fatty acids, polysaccharides, proteins, minerals, pigments, and vitamins, which are highly valued products with pharmaceutical applications (Sathasivam et al., 2019; Ugya et al., 2020a). These metabolites act as important antioxidants used for the treatment of illness such as inflammation and immunomodulating actions (Pham-Huy et al., 2008).

Microalgae biomass production is important in the success of the microalgae-based industry (Araújo et al., 2021). This is necessary, because optimising the production of microalgae biomass will lead to tremendous advancement in algae biotechnology (Hannon et al., 2010). This algae biotechnology development will lead to the easy commercialisation of microalgae applications (Fabris et al., 2020). The optimisation of the production of microalgae biomass is the most important step in the harnessing of microalgae resources, because it reduces the cost of the production of microalgae biomass and increases the efficiency of microalgae resource utilisation (Chu, 2017). The industrial application of microalgae biomass includes the production of cosmetics, health products, fertilisers, biofuel, feeds and food (Milledge, 2011). Microalgae biomass is also an important tool used in the treatment of wastewater (Mohsenpour et al., 2021). The current paper is aimed at reviewing the progress and prospects of microalgae resource modelling and optimisation as a tool for sustainable biotechnology.

MICROALGAE BIOMASS PRODUCTION

Microalgae biomass production is usually accomplished using an open or closed system. The open system used in microalgae biomass production is a pond-like type of system, with the majority of studies focusing on the use of tanks (Costa & de Morais, 2014). Although, the open systems are used in large scale microalgae culture due to low power demand, easy cleaning process, low construction cost and appropriate scale-up (Costa & de Morais, 2014). There are limitations in its application due to adverse environmental conditions and greenhouse emission which affect the ability of microalgae to fix CO_2 in the system, leading to low biomass production by the microalgae (Murthy, 2011). The closed system of microalgae biomass production involves the use of a closed photoreactor for the cultivation of microalgae biomass (Xu et al., 2009). This system has high microalgae biomass productivity and a high reduction in the risks of contamination (Sharma et al., 2022). The system favours the ability of microalgae to fix and convert CO_2 into microalgae biomass and aids in the production of bioresources of interest (Ebhodaghe et al., 2022).

The mechanism involved in the production of biomass in both open and closed systems by microalgae depends on the mode of nutrition of the microalgae (Randrianarison & Ashraf, 2017). This is because the growth requirements of autotrophic microalgae tend to differ from those of heterotrophic microalgae. Similarly, the growth conditions of mixotrophic microalgae tend to differ from those of autotrophic and heterotrophic microalgae (Jareonsin & Pumas, 2021; Roostaei et al., 2018). The mechanism of biomass production by autotrophic microalgae involves the utilisation of CO_2 and water in the presence of sunlight (Fig. 1) (Mohammad Mirzaie et al., 2016). The process also involves the utilisation of nitrate, phosphate, and other essential elements present in open and closed systems. The autotrophic culture method is considered the most economical and most viable method because a high biomass yield is achieved (Silva et al., 2021). The mechanism involve in the production of biomass by heterotrophic microalgae by the utilisation of organic carbon substrate as source of carbon and energy (Morales-Sánchez et al., 2017). The process occurs in dark, because it is independent of light. The carbon source used to grow heterotrophic microalgae biomass includes glycerol, glucose and acetate. However a number of studies have shown how heterotrophic microalgae biomass is grown using wastewater as the source of organic carbon and energy source. The heterotrophic microalgae biomass production method is the most used method on commercial scale production of microalgae biomass because the method favours higher accumulation of lipid, thus better suited for biofuel production (Ranjith Kumar et al., 2015). The amount of protein and carbohydrate produce in microalgae biomass using the heterotrophic method is also higher and this is attributed to the utilisation of high nutrient loads, compared to the microalgae biomass resulting from autotrophic microalgae (Guldhe et al., 2017).

Mixotrophic method of microalgae biomass production involves the use of light and organic source of energy as energy sources for the production of microalgae biomass. The method also utilises both inorganic and organic carbon, leading to higher biomass production. The method produces the microalgae biomass that accumulates more lipids, carbohydrate, proteins and other biomolecules because the method overcomes the limitation of both heterotrophic and autotrophic method of microalgae biomass production because both principles are combined in the mixotrophic method (Zhan et al., 2017).

MODELLING AND OPTIMISATION OF MICROALGAE BIOMASS PRODUCTION

A number of microalgae base models have been developed. These models are based on key factors that affect microalgae biomass production, including CO_2 sequestration, nutrients, culture system, and light. The first work on microalgae growth kinetics was first proposed by Droop (1983). The model proposed shows the relationship between the internal substrate in microalgae cells and the growth process. The Droop model is described in equation (1):

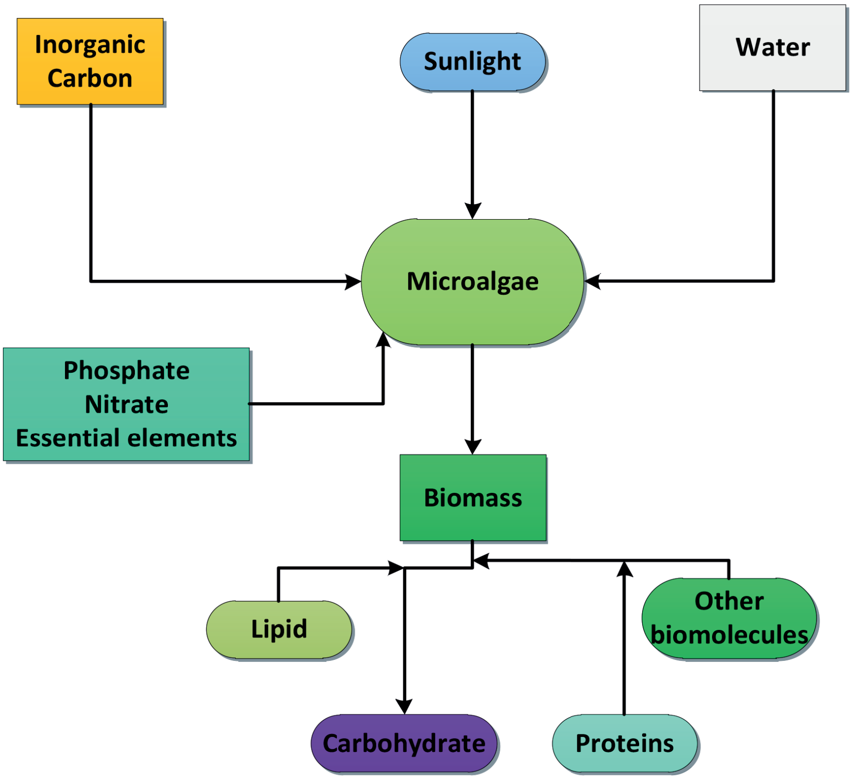

Figure 1. Mechanism of biomass production by autotrophic microalgae

$$\mu = \mu_m(1 - \frac{K_q}{Q}) \quad (1)$$

where: μ – specific growth rate,
μ_m – theoretical growth rate at infinite quota,
K_q – minimum quota,
Q – cell quota.

After the work of Droop (1983), many studies on mathematical modelling and prediction of biomass production were published (Packer et al., 2011). Although the majority of these models describe microalgae biomass production using the Monod formulation rather than the direct use of the Droop model, measurement of the external substrate is easier and more accurate than internal cell quotas (Davidson & Gurney, 1999). These models are based on experimental data which relate microalgae growth and the concentration of substrate in the culture medium (Eze et al., 2018). The emergence of dynamic models is due to the fact that changes in microalgae growth could be due to more than two factors (Lee et al., 2015).

MODELLING OF CO_2 SEQUESTRATION FOR MICROALGAE BIOMASS PRODUCTION

Microalgae tend to sustain the atmosphere by utilising CO_2 for biomass production (Prasad et al., 2021). The fixing of CO_2 by microalgae tends to increase the amount of lipid accumulation in the biomass of microalgae, thus enhancing the potential of the microalgae biomass for use in biofuel production (Onyeaka et al., 2021). To enhance the ability of microalgae to fix CO_2 for biomass production, it is important to optimise the rate of CO_2 fixation under optimal conditions (Gerotto et al., 2020). The modelling of microalgae systems will give a clear understanding of microalgae behaviour and optimal operation parameters (Gerotto et al., 2020). The study involving the modelling of the fixing of CO_2 by microalgae for biomass production is usually interpreted by using microalgae in the removal of CO_2 from the flue gases of a power plant (Kroumov et al., 2016). Other gases present in the flue gas include SO_2 and NO_2, although its composition depends largely on what is burnt (Songolzadeh et al., 2014). To develop and effective model for CO_2 fixation during biomass production, there is need to first develop a pure kinetic model of the tolerance of CO_2 in air by microalgae and the development of real kinetic on the utilisation of CO_2 from flue gas (Daneshvar et al., 2022). The development of pure kinetic model is important, because it occurs in lab scale and involves real experimental design which leads to the understanding of water chemistry (Eze et al., 2018). Another important issue in carbon sequestration is the uptake of CO_2 from flue gases and how it liquefies in the liquid phase as a function of pH (Leung et al., 2014). The pH is an important tool in the modelling of CO_2 fixing rate by microalgae, because gases such as SO_2 and NO_2 are gases in flue that are useful in microalgae photosynthesis; hence, both SO_2 and NO_2 are important in CO_2 fixing modelling (Duarte et al., 2016). The utilisation of CO_2 and increase in microalgae biomass production in most microalgae species is between pH of 6–11 (Duarte et al., 2016). The models used to predict CO_2 fixing in microalgae is represented in the equations (2) and (3). Equation (2) is Monod model which shows the monotonic behaviour, because it fails to take into consideration possible inhibition that could occur due to high substrate concentration. Equation (3) is the Haldane-like model which display a non-monotonic behaviour which describe inhibition at high substrate concentration (Kasiri et al., 2015).

$$\mu = \mu_m \frac{S}{K_s + S} \quad (2)$$

$$\mu = \mu_m \frac{S}{K_s + S + S^2/K_I} \quad (3)$$

where: μ – specific growth rate,
μ_m – maximum growth rate,
S – substrate concentration,
K_S – half substrate saturation constant,
K_I – inhibition parameter.

MODELLING OF LIGHT INTENSITY FOR MICROALGAE BIOMASS PRODUCTION

Microalgae are able to produce biomass at low light intensity (Nzayisenga et al., 2020). This is because light intensity increases the ability of microalgae to fixed CO_2. The modelling of light shows the effect of light on the biomass production of microalgae, because at cellular level it is one of the important tools used by microalgae for photosynthesis (Alishah Aratboni et al., 2019). The linkage between light intensity and photosynthesis in the cell of microalgae is represented as Pl, where l denotes light intensity and P denotes photosynthesis. The Pl is divided into 3 distinct regimes which are light limited regime, light saturated regime and light inhibited regime (Liu et al., 2013). The rate at which photosynthesis occurs is usually proportional to the rate of light intensity at the light limited regimes (Béchet et al., 2013). This is due to the fact that the rate of photosynthesis is limited by the amount of captured protons (Béchet et al., 2013). The rate of photosynthesis in microalgae culture is usually maximal and independent of light intensity at the light saturated regimes. This is due to the fact that the light intensity needed for photosynthesis have reached the saturated thresholds. The rate of photosynthesis in microalgae culture tends to decrease with increasing light intensity at light inhibition regime (Metsoviti et al., 2019). This decrease in the rate of photosynthesis is due to the deactivation of key protein important for photosynthesis due to the effect of increasing light intensity beyond an inhibitory threshold (McClain & Sharkey, 2019). There is no universal model for the description of Pl, but the reviews by Bechet et al. (2013) and Kroumov et al. (2016) have summarised some interesting models used to show the effect of light intensity on microalgae biomass production. The kinetic model developed thus far can be classified into 3 based on theoretical knowledge, namely type I model, type II model and type II model (Scheufele et al., 2018). The type I model shows that the rate of photosynthesis in well-mixed microalgae cultures is expressed as a function of the average light intensity within the culture. The idea behind this strategy is that individual microalgae cells in a well-mixed system are exposed to the same light intensity and, thus, have the same average rate of photosynthesis. However, empirical studies have demonstrated that the kinetic parameters associated with these models are actually functions of operating conditions, such as cell concentration, incident light intensity, or system size (Masojídek et al., 2021). The type II model shows the effect of light gradients on the local rate of photosynthesis of the microalgae. These models are built by: (i) quantifying the light distribution within the culture (ii) establishing a biological model that expresses the local rate of photosynthesis as a function of the local light intensity; and (iii) adding the local rates of photosynthesis to obtain the global rate of photosynthesis (Abdel-Raouf et al., 2012). The type III shows the rate of photosynthesis of an individual algal cell is a function of its light history. Their model shows that microalgae cell tend to experienced light intensity overtime as it moves in the system. These models are usually built by (i) determining the light history of microalgae cells; (ii) using a dynamic biological model to calculate the rate of photosynthesis of individual microalgae cells; and (iii) adding the rates of photosynthesis of individual microalgae cells to calculate the total rate of photosynthesis in the cultivation system (Kroumov et al., 2016).

MODELLING OF NUTRIENTS FOR MICROALGAE BIOMASS PRODUCTION

These nutrients play a key role in microalgae production of biomass (Delgadillo-Mirquez et al., 2016). Biomass production of microalgae correlates positively with nutrient concentration, particularly nitrogen and phosphorus which must be sufficient for microalgae to achieve maximal biomass productivity (Yaakob et al., 2021). The modelling of the nutrients in microalgae system tends to focus on the concentration nitrogen and phosphorus (Yaakob et al., 2021). The equation (4–7) below represents the model use in the modelling and prediction of nitrogen and phosphorus in the system.

Nitrogen models

$$\mu_{\mathrm{MCA}} = \mu_m\left(1 - \frac{qnx_{min}}{qnx}\right) \tag{4}$$

where: μ_m – maximum specific growth rate,
qnx – internal nitrogen cell quota,
qnx_{min} – minimum nitrogen cell quota.

$$\mu_{MCA} = \mu_m \frac{S_n}{K_{sn} + S_n} \tag{5}$$

where: μ_m – maximum specific growth rate,
S_n – nitrogen concentration,
K_{sn} – half-saturation constant for nitrogen.

Phosphorus model

$$\mu_{MCA} = \mu_m \frac{S_p}{K_{sp} + S_p} \tag{6}$$

where: μ_m – maximum specific growth rate,
S_p – phosphorus concentration,
K_{sp} – half-saturation constant phosphorus.

$$\mu_{MCA} = \mu_m\left(1 - \frac{qpx_{min}}{qpx}\right) \tag{7}$$

where: μ_m – maximum specific growth rate,
qpx – internal phosphorus cell quota,
qpx_{min} – minimum phosphorus cell quota.

MODELLING OF PHOTOBIOREACTOR FOR MICROALGAE BIOMASS PRODUCTION

The modelling of the behaviour of photobioreactors is imperative for the studies involving large-scale production of microalgae biomass (Sforza et al., 2014). This is because modelling of the photobioreactor will increase the microalgae biomass optimisation level, saving time and investment (Slegers et al., 2011). Photobioreactor is important for microalgae biomass production, because it controls such parameters as light and temperature which influence the ability of microalgae to produce biomass. For the modelling of photobioreactors for sustainable production of microalgae biomass, the latitude of the photobioreactor, the orientation of the photobioreactor, the variations in light due to the diurnal cycle, the variations in light intensity caused by seasonal changes, the influence of shadows of nearby objects, the ability of the photobioreactor wall and ground to reflect light, the effect of absorption of light by microalgae on the light gradient in the photobioreactor, the type of microalgale species used, the effect of light gradients on the growth of microalgae and dark respiration should be taken into consideration (Slegers et al., 2011; Vasile et al., 2021).

THE ROLE OF MICROALGAE BIOMASS IN SUSTAINABLE BIOTECHNOLOGY

The use of microalgae biomass as a resources will help to enhance the present day needs and without depleting the resources needed by the future generation (Pathak et al., 2018). This is because microalgae biomass is an important tool for the production of aquaculture feeds, nutritional supplements, pharmaceutical products, biomedical tools, and biofuels (Ugya et al., 2022). It is also widely used for phycoremediation of contaminated water (Ugya, 2021; Ugya et al., 2021a). The production of aquaculture feeds from forage fish has implications for the sustainability of the biota of fresh and marine ecosystems due to food chain disruption (Jennings et al., 2016). The production of aquaculture feeds from terrestrial plants also tends to negatively affect the sustainable utilisation of resources (Froehlich et al., 2018). The process is associated with continuous deforestation and high usage of freshwater (Kong et al., 2020). The production of aquaculture feeds using terrestrial plants causes a shortage of vital food resources, such as soybeans, corn, cottonseed, peas, wheat, and barley, which are food resources that are in high demand in our present world (Delgado et al., 2021; Kokou & Fountoulaki, 2018; Zhou et al., 2018). The use of microalgae biomass as an aquaculture feed will solve the problems associated with the use of forage fish and terrestrial plant materials, because the net biomass production of microalgae is higher than terrestrial plants. The biomass of microalgae also tends to have little or no food-use characteristics (Nagappan et al., 2021). The production of microalgae biomass does not largely depend on freshwater, because microalgae can grow faster in wastewater. Other metabolic profiles of microalgae biomass qualify it as an effective resource for the production of aquaculture feeds. A detailed study on the efficacy of microalgae biomass for the production of aquaculture feeds has been well presented by Nagappan et al., (2021). The increasing concern over the substitute for fossil fuel due to its high price and environmental fate has increased the tendency towards the use of biofuel (Reid et al., 2020). Energy policymakers believe that using biofuels will alleviate the burden of consuming over 86 million barrels of crude oil per day, reducing the economic hardship associated with crude oil price increases (Jeswani et al., 2020). The use of biofuel will also eliminate the negative environmental impact associated with the use of crude oil, as the usage of fossil fuels accounts for more than 25% of CO_2 emissions. The use of biofuel will also aid in the economic growth of developing countries that lack the technological know-how to effectively utilise and manage fossil fuels (Hill et al., 2006). The incessant increase in the price of food crops and deforestation has raised public debate over the importance of biofuels due to the massive utilisation of terrestrial plants for biofuel production (Popp et al., 2016). The use of terrestrial plants for biofuel production will likely increase the greenhouse gases, rather than reduce them, due to the role of terrestrial plants in the carbon cycle (Field John et al., 2020). The debate on the applicability of biofuel has been centred on food vs. fuel, greenhouse gases and ecosystem services (Milner et al., 2016). The use of microalgae biomass will eradicate the problems associated with the utilisation of food crops for biofuel production (Khan et al., 2018b). This is because microalgae grow over 100 times faster than terrestrial plants (Ganesan et al., 2020). Microalgae are able to accumulate more lipids in their biomass than terrestrial plants, thereby making them more efficient for biofuel production (Tan & Lee, 2016). The use of microalgae will also eradicate the problems associated with greenhouse emissions and ecosystem services, because microalgae are able to sequestrate inorganic carbon for biomass production (Molazadeh et al., 2019). The use of microalgae biomass for biofuel production will also prevent deforestation and the problems associated with it (Medipally et al., 2015).

CONCLUSIONS

The current review showed the role of modelling and optimisation of microalgae biomass production for a sustainable biotechnology. It was shown that microalgae biomass is an important component for industrial revolution that will lead to sustainable development. Microalgae biomass is important in renewable energy production and other economic viable materials such as aquaculture feeds, nutritional supplements, pharmaceutical products, biomedical tools, and biofuels. Microalgae are an emerging tool used in the phycoremediation of wastewater and reduction of high CO_2 level. The modelling and optimisation of microalgae biomass production will help to upscale the production of the microalgal based fuel and bioproducts from model scale to the money-making level.

REFERENCES

1. Abdel-Raouf, N., Al-Homaidan, A.A., Ibraheem, I.B.M. 2012. Microalgae and wastewater treatment. Saudi Journal of Biological Sciences, 19(3), 257–275.
2. Acién, F.G., Molina, E., Fernández-Sevilla, J.M., Barbosa, M., Gouveia, L., Sepúlveda, C., Bazaes, J., Arbib, Z. 2017. 20 - Economics of microalgae production. in: Microalgae-Based Biofuels and Bioproducts, (Eds.) C. Gonzalez-Fernandez, R. Muñoz, Woodhead Publishing, 485–503.
3. Alishah Aratboni, H., Rafiei, N., Garcia-Granados, R., Alemzadeh, A., Morones-Ramírez, J.R. 2019. Biomass and lipid induction strategies in microalgae for biofuel production and other applications. Microbial Cell Factories, 18(1), 178.
4. Alvarez, A.L., Weyers, S.L., Goemann, H.M., Peyton, B.M., Gardner, R.D. 2021. Microalgae, soil and plants: A critical review of microalgae as renewable resources for agriculture. Algal Research, 54, 102200.
5. Amaro, H.M., Sousa-Pinto, I., Malcata, F.X., Guedes, A.C. 2017. Microalgal fatty acids – from harvesting until extraction. In: Microalgae-Based Biofuels and Bioproducts, (Eds.) C. Gonzalez-Fernandez, R. Muñoz, Woodhead Publishing, 369–400.
6. Araújo, R., Vázquez Calderón, F., Sánchez López, J., Azevedo, I.C., Bruhn, A., Fluch, S., Garcia Tasende, M., Ghaderiardakani, F., Ilmjärv, T., Laurans, M., Mac Monagail, M., Mangini, S., Peteiro, C., Rebours, C., Stefansson, T., Ullmann, J. 2021. Current Status of the Algae Production Industry in Europe: An Emerging Sector of the Blue Bioeconomy, 7.
7. Balan, V. 2014. Current challenges in commercially producing biofuels from lignocellulosic biomass. ISRN biotechnology, 2014, 463074–463074.
8. Béchet, Q., Shilton, A., Guieysse, B. 2013. Modeling the effects of light and temperature on algae growth: State of the art and critical assessment for productivity prediction during outdoor cultivation. Biotechnology Advances, 31(8), 1648–1663.
9. Chu, W.-L. 2017. Strategies to enhance production of microalgal biomass and lipids for biofuel feedstock. European Journal of Phycology, 52(4), 419–437.
10. Costa, J.A.V., de Morais, M.G. 2014. Chapter 1 - An Open Pond System for Microalgal Cultivation. in: Biofuels from Algae, (Eds.) A. Pandey, D.-J. Lee, Y. Chisti, C.R. Soccol, Elsevier. Amsterdam, 1–22.
11. Daneshvar, E., Wicker, R.J., Show, P.-L., Bhatnagar, A. 2022. Biologically-mediated carbon capture and utilization by microalgae towards sustainable CO2 biofixation and biomass valorization – A review. Chemical Engineering Journal, 427, 130884.
12. Davidson, K., Gurney, W.S.C. 1999. An investigation of non-steady-state algal growth. II. Mathematical modelling of co-nutrient-limited algal growth. Journal of Plankton Research, 21.
13. Delgadillo-Mirquez, L., Lopes, F., Taidi, B., Pareau, D. 2016. Nitrogen and phosphate removal from wastewater with a mixed microalgae and bacteria culture. Biotechnology Reports, 11, 18–26.
14. Delgado, E., Valles-Rosales, D.J., Flores, N.C., Reyes-Jáquez, D. 2021. Evaluation of fish oil content and cottonseed meal with ultralow gossypol content on the functional properties of an extruded shrimp feed. Aquaculture Reports, 19, 100588.
15. Dixon, C., Wilken, L.R. 2018. Green microalgae biomolecule separations and recovery. Bioresources and Bioprocessing, 5(1), 14.
16. Duarte, J.H., Fanka, L.S., Costa, J.A.V. 2016. Utilization of simulated flue gas containing CO_2, SO_2, NO and ash for Chlorella fusca cultivation. Bioresource Technology, 214, 159–165.

17. Ebhodaghe, S.O., Imanah, O.E., Ndibe, H. 2022. Biofuels from microalgae biomass: A review of conversion processes and procedures. Arabian Journal of Chemistry, 15(2), 103591.
18. Eze, V.C., Velasquez-Orta, S.B., Hernández-García, A., Monje-Ramírez, I., Orta-Ledesma, M.T. 2018. Kinetic modelling of microalgae cultivation for wastewater treatment and carbon dioxide sequestration. Algal Research, 32, 131–141.
19. Fabris, M., Abbriano, R.M., Pernice, M., Sutherland, D.L., Commault, A.S., Hall, C.C., Labeeuw, L., McCauley, J.I., Kuzhiuparambil, U., Ray, P., Kahlke, T., Ralph, P.J. 2020. Emerging Technologies in Algal Biotechnology: Toward the Establishment of a Sustainable, Algae-Based Bioeconomy, 11.
20. Field John, L., Richard Tom, L., Smithwick Erica, A.H., Cai, H., Laser Mark, S., LeBauer David, S., Long Stephen, P., Paustian, K., Qin, Z., Sheehan John, J., Smith, P., Wang Michael, Q., Lynd Lee, R. 2020. Robust paths to net greenhouse gas mitigation and negative emissions via advanced biofuels. Proceedings of the National Academy of Sciences, 117(36), 21968–21977.
21. Froehlich, H.E., Runge, C.A., Gentry, R.R., Gaines, S.D., Halpern, B.S. 2018. Comparative terrestrial feed and land use of an aquaculture-dominant world. Proceedings of the National Academy of Sciences of the United States of America, 115(20), 5295–5300.
22. Ganesan, R., Manigandan, S., Samuel, M.S., Shanmuganathan, R., Brindhadevi, K., Lan Chi, N.T., Duc, P.A., Pugazhendhi, A. 2020. A review on prospective production of biofuel from microalgae. Biotechnology reports (Amsterdam, Netherlands), 27, e00509–e00509.
23. Gerotto, C., Norici, A., Giordano, M. 2020. Toward Enhanced Fixation of CO_2 in Aquatic Biomass: Focus on Microalgae, 8.
24. Guldhe, A., Ansari, F.A., Singh, P., Bux, F. 2017. Heterotrophic cultivation of microalgae using aquaculture wastewater: A biorefinery concept for biomass production and nutrient remediation. Ecological Engineering, 99, 47–53.
25. Hannon, M., Gimpel, J., Tran, M., Rasala, B., Mayfield, S. 2010. Biofuels from algae: challenges and potential. Biofuels, 1(5), 763–784.
26. Hill, J., Nelson, E., Tilman, D., Polasky, S., Tiffany, D. 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. Proceedings of the National Academy of Sciences, 103(30), 11206–11210.
27. Jareonsin, S., Pumas, C. 2021. Advantages of Heterotrophic Microalgae as a Host for Phytochemicals Production, 9.
28. Jennings, S., Stentiford, G.D., Leocadio, A.M., Jeffery, K.R., Metcalfe, J.D., Katsiadaki, I., Auchterlonie, N.A., Mangi, S.C., Pinnegar, J.K., Ellis, T., Peeler, E.J., Luisetti, T., Baker-Austin, C., Brown, M., Catchpole, T.L., Clyne, F.J., Dye, S.R., Edmonds, N.J., Hyder, K., Lee, J., Lees, D.N., Morgan, O.C., O'Brien, C.M., Oidtmann, B., Posen, P.E., Santos, A.R., Taylor, N.G.H., Turner, A.D., Townhill, B.L., Verner-Jeffreys, D.W. 2016. Aquatic food security: insights into challenges and solutions from an analysis of interactions between fisheries, aquaculture, food safety, human health, fish and human welfare, economy and environment. Fish and Fisheries, 17(4), 893–938.
29. Jeswani, H.K., Chilvers, A., Azapagic, A. 2020. Environmental sustainability of biofuels: a review. Proceedings. Mathematical, physical, and engineering sciences, 476(2243), 20200351–20200351.
30. Kasiri, S., Ulrich, A., Prasad, V. 2015. Kinetic modeling and optimization of carbon dioxide fixation using microalgae cultivated in oil-sands process water. Chemical Engineering Science, 137, 697–711.
31. Khan, M.I., Shin, J.H., Kim, J.D. 2018a. The promising future of microalgae: current status, challenges, and optimization of a sustainable and renewable industry for biofuels, feed, and other products. Microbial Cell Factories, 17(1), 36.
32. Khan, M.I., Shin, J.H., Kim, J.D. 2018b. The promising future of microalgae: current status, challenges, and optimization of a sustainable and renewable industry for biofuels, feed, and other products. Microbial cell factories, 17(1), 36–36.
33. Khanna, M., Crago, C.L., Black, M. 2011. Can biofuels be a solution to climate change? The implications of land use change-related emissions for policy. Interface focus, 1(2), 233–247.
34. Kokou, F., Fountoulaki, E. 2018. Aquaculture waste production associated with antinutrient presence in common fish feed plant ingredients. Aquaculture, 495, 295–310.
35. Kong, W., Huang, S., Yang, Z., Shi, F., Feng, Y., Khatoon, Z. 2020. Fish Feed Quality Is a Key Factor in Impacting Aquaculture Water Environment: Evidence from Incubator Experiments. Scientific reports, 10(1), 187–187.
36. Kroumov, A.D., Módenes, A.N., Trigueros, D.E.G., Espinoza-Quiñones, F.R., Borba, C.E., Scheufele, F.B., Hinterholz, C.L. 2016. A systems approach for CO2 fixation from flue gas by microalgae—Theory review. Process Biochemistry, 51(11), 1817–1832.
37. Lee, E., Jalalizadeh, M., Zhang, Q. 2015. Growth kinetic models for microalgae cultivation: A review. Algal Research, 12, 497–512.
38. Leung, D.Y.C., Caramanna, G., Maroto-Valer, M.M. 2014. An overview of current status of carbon dioxide capture and storage technologies. Renewable and Sustainable Energy Reviews, 39, 426–443.
39. Liu, S.L., Ma, M.D., Pan, Y.Z., Wei, L.L., He, C.X., Yang, K.M. 2013. Effects of light regime on the

growth and photosynthetic characteristics of Alnus formosana and A. cremastogyne seedlings. Ying Yong Sheng Tai Xue Bao, 24(2), 351–358.

40. Masojídek, J., Ranglová, K., Lakatos, G.E., Silva Benavides, A.M., Torzillo, G. 2021. Variables Governing Photosynthesis and Growth in Microalgae Mass Cultures. Processes, 9(5).
41. McClain, A.M., Sharkey, T.D. 2019. Triose phosphate utilization and beyond: from photosynthesis to end product synthesis. Journal of experimental botany, 70(6), 1755–1766.
42. Medipally, S.R., Yusoff, F.M., Banerjee, S., Shariff, M. 2015. Microalgae as sustainable renewable energy feedstock for biofuel production. BioMed research international, 2015, 519513–519513.
43. Metsoviti, M.N., Papapolymerou, G., Karapanagiotidis, I.T., Katsoulas, N. 2019. Effect of light intensity and quality on growth rate and composition of *Chlorella vulgaris*. Plants (Switzerland), 9(1), 31.
44. Milledge, J.J. 2011. Commercial application of microalgae other than as biofuels: a brief review. Reviews in Environmental Science and Bio/Technology, 10(1), 31–41.
45. Milner, S., Holland, R.A., Lovett, A., Sunnenberg, G., Hastings, A., Smith, P., Wang, S., Taylor, G. 2016. Potential impacts on ecosystem services of land use transitions to second-generation bioenergy crops in GB. Global change biology. Bioenergy, 8(2), 317–333.
46. Mohammad Mirzaie, M.A., Kalbasi, M., Mousavi, S.M., Ghobadian, B. 2016. Investigation of mixotrophic, heterotrophic, and autotrophic growth of Chlorella vulgaris under agricultural waste medium. Prep Biochem Biotechnol, 46(2), 150–156.
47. Mohsenpour, S.F., Hennige, S., Willoughby, N., Adeloye, A., Gutierrez, T. 2021. Integrating microalgae into wastewater treatment: A review. Science of The Total Environment, 752, 142168.
48. Molazadeh, M., Ahmadzadeh, H., Pourianfar, H.R., Lyon, S., Rampelotto, P.H. 2019. The Use of Microalgae for Coupling Wastewater Treatment With CO(2) Biofixation. Frontiers in bioengineering and biotechnology, 7, 42–42.
49. Morales-Sánchez, D., Martinez-Rodriguez, O.A., Martinez, A. 2017. Heterotrophic cultivation of microalgae: production of metabolites of commercial interest. Journal of Chemical Technology & Biotechnology, 92(5), 925–936.
50. Muralikrishna, I.V., Manickam, V. 2017. Chapter Three - Natural Resource Management and Biodiversity Conservation. in: Environmental Management, (Eds.) I.V. Muralikrishna, V. Manickam, Butterworth-Heinemann, 23–35.
51. Murthy, G.S. 2011. Chapter 18 - Overview and Assessment of Algal Biofuels Production Technologies. in: Biofuels, (Eds.) A. Pandey, C. Larroche, S.C. Ricke, C.-G. Dussap, E. Gnansounou, Academic Press. Amsterdam, 415–437.
52. Nagappan, S., Das, P., AbdulQuadir, M., Thaher, M., Khan, S., Mahata, C., Al-Jabri, H., Vatland, A.K., Kumar, G. 2021. Potential of microalgae as a sustainable feed ingredient for aquaculture. Journal of Biotechnology, 341, 1–20.
53. Nzayisenga, J.C., Farge, X., Groll, S.L., Sellstedt, A. 2020. Effects of light intensity on growth and lipid production in microalgae grown in wastewater. Biotechnology for Biofuels, 13(1), 4.
54. Onyeaka, H., Miri, T., Obileke, K., Hart, A., Anumudu, C., Al-Sharify, Z.T. 2021. Minimizing carbon footprint via microalgae as a biological capture. Carbon Capture Science & Technology, 1, 100007.
55. Packer, A., Li, Y., Andersen, T., Hu, Q., Kuang, Y., Sommerfeld, M. 2011. Growth and neutral lipid synthesis in green microalgae: A mathematical model. Bioresource technology, 102, 111–117.
56. Pathak, J., Rajneesh, Maurya, P.K., Singh, S.P., Häder, D.-P., Sinha, R.P. 2018. Cyanobacterial Farming for Environment Friendly Sustainable Agriculture Practices: Innovations and Perspectives, 6.
57. Pham-Huy, L.A., He, H., Pham-Huy, C. 2008. Free radicals, antioxidants in disease and health. International Journal of Biomedical Science: IJBS, 4(2), 89–96.
58. Popp, J., Harangi-Rákos, M., Gabnai, Z., Balogh, P., Antal, G., Bai, A. 2016. Biofuels and Their Co-Products as Livestock Feed: Global Economic and Environmental Implications. Molecules (Basel, Switzerland), 21(3), 285–285.
59. Prasad, R., Gupta, S.K., Shabnam, N., Oliveira, C.Y-.B., Nema, A.K., Ansari, F.A., Bux, F. 2021. Role of microalgae in global CO_2 sequestration: Physiological mechanism, recent development, challenges, and future prospective. Sustainability, 13(23).
60. Raja, R., Coelho, A., Hemaiswarya, S., Kumar, P., Carvalho, I.S., Alagarsamy, A. 2018. Applications of microalgal paste and powder as food and feed: An update using text mining tool. Beni-Suef University Journal of Basic and Applied Sciences, 7(4), 740–747.
61. Randrianarison, G., Ashraf, M.A. 2017. Microalgae: a potential plant for energy production. Geology, Ecology, and Landscapes, 1(2), 104–120.
62. Ranjith Kumar, R., Hanumantha Rao, P., Arumugam, M. 2015. Lipid Extraction Methods from Microalgae: A Comprehensive Review, 2.
63. Reid, W.V., Ali, M.K., Field, C.B. 2020. The future of bioenergy. Global Change Biology, 26(1), 274–286.
64. Roostaei, J., Zhang, Y., Gopalakrishnan, K., Ochocki, A.J. 2018. Mixotrophic microalgae biofilm: A novel algae cultivation strategy for improved productivity and cost-efficiency of biofuel feedstock production. Scientific Reports, 8(1), 12528–12528.

65. Sathasivam, R., Radhakrishnan, R., Hashem, A., Abd_Allah, E.F. 2019. Microalgae metabolites: A rich source for food and medicine. Saudi Journal of Biological Sciences, 26(4), 709–722.
66. Scheufele, F.B., Hinterholz, C.L., Zaharieva, M.M., Najdenski, H.M., Módenes, A.N., Trigueros, D.E.G., Borba, C.E., Espinoza-Quiñones, F.R., Kroumov, A.D. 2018. Complex mathematical analysis of photobioreactor system. Engineering in life sciences, 19(12), 844–859.
67. Sforza, E., Enzo, M., Bertucco, A. 2014. Design of microalgal biomass production in a continuous photobioreactor: An integrated experimental and modeling approach. Chemical Engineering Research and Design, 92(6), 1153–1162.
68. Sharma, P., Gujjala, L.K.S., Varjani, S., Kumar, S. 2022. Emerging microalgae-based technologies in biorefinery and risk assessment issues: Bioeconomy for sustainable development. Science of The Total Environment, 813, 152417.
69. Silva, T.L., Moniz, P., Silva, C., Reis, A. 2021. The role of heterotrophic microalgae in waste conversion to biofuels and bioproducts. Processes, 9(7).
70. Singh, J.S., Kumar, A., Rai, A.N., Singh, D.P. 2016. Cyanobacteria: A precious bio-resource in agriculture, ecosystem, and environmental sustainability. Frontiers in microbiology, 7, 529–529.
71. Singh, R., Parihar, P., Singh, M., Bajguz, A., Kumar, J., Singh, S., Singh, V.P., Prasad, S.M. 2017. Uncovering potential applications of cyanobacteria and algal metabolites in biology. Agriculture and Medicine: Current Status and Future Prospects, 8.
72. Slegers, P.M., Wijffels, R.H., van Straten, G., van Boxtel, A.J.B. 2011. Design scenarios for flat panel photobioreactors. Applied Energy, 88(10), 3342–3353.
73. Songolzadeh, M., Soleimani, M., Takht Ravanchi, M., Songolzadeh, R. 2014. Carbon dioxide separation from flue gases: A technological review emphasizing reduction in greenhouse gas emissions. The Scientific World Journal, 2014, 828131.
74. Tan, K.W.M., Lee, Y.K. 2016. The dilemma for lipid productivity in green microalgae: importance of substrate provision in improving oil yield without sacrificing growth. Biotechnology for Biofuels, 9, 255–255.
75. Ugya, A.Y. 2021. The efficiency and antioxidant response of microalgae biofilm in the phycoremediation of wastewater resulting from tannery, textile, and dyeing activities. International Aquatic Research, 13(4), 289–300.
76. Ugya, A.Y., Ajibade, F.O., Hua, X. 2021a. The efficiency of microalgae biofilm in the phycoremediation of water from River Kaduna. Journal of Environmental Management, 295, 113109.
77. Ugya, A.Y., Ari, H.A., Hua, X. 2021b. Microalgae biofilm formation and antioxidant responses to stress induce by Lemna minor L., Chlorella vulgaris, and Aphanizomenon flos-aquae. Ecotoxicology and Environmental Safety, 221, 112468.
78. Ugya, A.Y., Hasan, D.u.B., Ari, H.A., Ajibade, F.O., Imam, T.S., Abba, A., Hua, X. 2020a. Natural freshwater microalgae biofilm as a tool for the clean-up of water resulting from mining activities. All Life, 13(1), 644–657.
79. Ugya, A.Y., Imam, T.S., Li, A., Ma, J., Hua, X. 2020b. Antioxidant response mechanism of freshwater microalgae species to reactive oxygen species production: a mini review. Chemistry and Ecology, 36(2), 174–193.
80. Ugya, A.Y., Meguellati, K., Aliyu, A.D., Abba, A., Musa, M.A. 2022. Microplastic stress induce bioresource production and response in microalgae: a concise review. Environmental Pollutants and Bioavailability, 34(1), 51–60.
81. Ugya, Y., Adamu., Hasan, D.u.B., Tahir, S.M., Imam, T.S., Ari, H.A., Hua, X. 2021c. Microalgae biofilm cultured in nutrient-rich water as a tool for the phycoremediation of petroleum-contaminated water. International Journal of Phytoremediation, 1–9.
82. Vale, M.A., Ferreira, A., Pires, J.C.M., Gonçalves, A.L. 2020. CO_2 capture using microalgae. In: Advances in Carbon Capture, (Eds.) M.R. Rahimpour, M. Farsi, M.A. Makarem, Woodhead Publishing, 381–405.
83. Vasile, N.S., Cordara, A., Usai, G., Re, A. 2021. Computational analysis of dynamic light exposure of unicellular algal cells in a flat-panel photobioreactor to support light-induced CO_2. Bioprocess Development, 12.
84. Xu, L., Weathers, P.J., Xiong, X.-R., Liu, C.-Z. 2009. Microalgal bioreactors: Challenges and opportunities. Engineering in Life Sciences, 9(3), 178–189.
85. Yaakob, M.A., Mohamed, R.M., Al-Gheethi, A., Aswathnarayana Gokare, R., Ambati, R.R. 2021. Influence of nitrogen and phosphorus on microalgal growth, biomass, lipid, and fatty acid production: An overview. Cells, 10(2).
86. Zafar, A.M., Javed, M.A., Aly Hassan, A., Mehmood, K., Sahle-Demessie, E. 2021. Recent updates on ions and nutrients uptake by halotolerant freshwater and marine microalgae in conditions of high salinity. Journal of Water Process Engineering, 44, 102382.
87. Zhan, J., Rong, J., Wang, Q. 2017. Mixotrophic cultivation, a preferable microalgae cultivation mode for biomass/bioenergy production, and bioremediation, advances and prospect. International Journal of Hydrogen Energy, 42(12), 8505–8517.
88. Zhou, Z., Ringø, E., Olsen, R.E., Song, S.K. 2018. Dietary effects of soybean products on gut microbiota and immunity of aquatic animals: A review. Aquaculture Nutrition, 24(1), 644–665.