**REVIEW ON :** **EFFECTS OF OPTIMIZATION OF LIGHT INTENSITY IN BATCH PHOTOBIOREACTOR FOR THE PRODUCTION OF MICROALGAE**

**Abstract:**

The following review paper explores the impact of optimizing light intensity in batch photobioreactors for microalgae biomass production. It investigates the potential of microalgae in environmental sustainability and industrial applications, emphasizing their importance in CO2 sequestration, bioresource production, and wastewater remediation. Additionally, the paper highlights the significance of microalgae biomass in medicine and industry, emphasizing its rich content of essential metabolites and bioactive compounds. The study concludes by emphasizing the importance of optimizing microalgae biomass production to advance the field of algae biotechnology and improve the feasibility of various applications and technologies.

**Introduction**

Microalgae, also known as autotrophic organisms, are highly efficient at extracting CO2 from the atmosphere through photosynthesis. This makes them incredibly valuable for various industrial applications, including cosmetics, health supplements, fertilizers, biofuels, animal feeds, and food products. Alongside their industrial uses, microalgae also play a crucial role in environmental management, particularly in wastewater treatment. They have the ability to remove contaminants and purify water, contributing to ecological balance and environmental sustainability. Recent studies have reviewed the potential of modeling and optimizing microalgae resources as a sustainable biotechnology tool. Specifically, the focus has been on modeling and optimizing microalgae biomass production by regulating light intensity and nutrients in photobioreactors. Microalgae also show promise for phytoremediation of wastewater and reducing high CO2 levels. By modeling and optimizing microalgae biomass production, we can increase the production of microalgae and its byproducts from a small scale to a commercially viable level.

**Microalgae's Potential for Environmental Sustainability and Industrial Uses**

Microalgae are a wide class of microscopic, unicellular organisms that can be either photosynthetic or heterotrophic(AlMallahi, Maryam Nooman, Sara Maen Asaad ., et.al 2022). They play a crucial role in aquatic ecosystems as primary producers, providing energy for a variety of freshwater and marine life.( Siddiki, S. Y. A., Mofijur,2022) . These organisms are highly adaptable and can thrive in various environments, including freshwater, marine, and hypersaline conditions. (Wang, Shi‐Kai, Amanda R 2015)

Autotrophic microalgae are efficient biological factories that help remove CO2 from the environment through photosynthesis.( Lehmuskero, Anni, Matilde Skogen Chauton, 2018).They can also convert CO2, nutrients, and solar energy into valuable bioresources such as proteins, carbohydrates, lipids, and other essential biomolecules.( Romagnoli, F., Weerasuriya-Arachchige, A. R. P. P., Paoli, R., Feofilovs, M., & Ievina, B. 2021).This process not only reduces carbon emissions but also provides important chemicals for various industries, including food, medicine, and biofuel production.(K. Iwamoto, and N. Abdullah 2021)

Heterotrophic microalgae and cyanobacteria fix atmospheric nitrogen and solubilize immobilized phosphorus in the soil to function as biofertilizers. (Bradley, T., Rajaeifar, M. A., Kenny 2023) They are advantageous for sustainable agriculture because they increase soil fertility and lessen the demand for synthetic fertilizers. (Costa, Jorge Alberto Vieira, et al.

Microalgae have a wide range of industrial applications, including production of food, animal feed, cosmetics, aquaculture products, medications, and biofuels.( Yaakob, Maizatul Azrina, et al. 2024) Their biomass, which can contain notable levels of lipids and carbohydrates, is seen as a potential sustainable alternative to conventional, non-renewable resources. (Amaro, H. M., Macedo, Â. C., & Malcata, F. X. 2012) .This makes them an important resource in the efforts to minimize dependency on fossil fuels and support long-term environmental and economic stability.( Brindley, Celeste, et al.2016)

**The Importance of Microalgal Biomass in Medicine and Industry**

The Importance of Microalgal Biomass in Medicine and Industry
Numerous essential metabolites, including proteins, polysaccharides, fatty acids, minerals, pigments, and vitamins, are plentiful in microalgal biomass.( Khan, Muhammad Imran 2018).These materials are used to make pharmaceuticals and nutritional supplements, and because of their possible applications in medical, they are in great demand.( Russell, Callum, Cristina Rodriguez, 2022) .Microalgae are a great resource for furthering pharmacological research and commercial development due to their vast range of bioactive chemicals.( Meenatchisundaram, Karthikeyan, et al 2024)These metabolites function as vital antioxidants and are utilized to treat a number of illnesses, such as immune system regulation and inflammation.[ Their potential applications in medicine and health promotion stem from the fact that their antioxidant qualities can fortify the body's defenses against oxidative stress.( Ansari, Faiz Ahmad, et al.2022)
The success of the microalgae-based enterprise depends on the generation of microalgae biomass. Enhancing biomass production is essential since it advances the area of algae biotechnology and raises the viability and effectiveness of many technologies and applications.( Goswami, R. K., Mehariya, S.,2023)

**Advancements in Microalgae Biotechnology: Optimizing Biomass Production and Industrial Applications**

Advancements in algal biotechnology will make it easier to commercialize microalgae applications. (de Jesus Raposo, Maria Filomena 2015 )Optimizing biomass production is crucial for fully utilizing microalgae resources, as it reduces production costs and improves resource utilization efficiency (Chu, 2017).( Gonçalves, J., Freitas, J., Fernandes, I., & Silva, P. 2023) This optimization is essential for ensuring the economic sustainability of microalgae and realizing their potential in various applications. (Chen, Cheng, et al.2022)

Microalgae biomass has numerous industrial uses, including food and animal feed production, fertilizer manufacturing, biofuel, cosmetics, and health product development.( Maltsev, Yevhen, et al. 2021) Its adaptability makes it important across a range of industries, boosting resource efficiency and sustainability.( Sforza, E., Pastore, M., Franke, S. M., & Barbera, E. 2020),( Hossain, S. Z., Sultana, et . , al 2022).

Microalgae biomass is also vital for wastewater treatment due to its effectiveness in cleaning water and removing contaminants. Choi, Hong Il, Young Joon Sung, Choi, Hong Il, Young Joon Sung 2019 )To demonstrate microalgae's potential as a sustainable tool in biotechnology, this research aims to investigate advancements in microalgae resource modeling and optimization.[28] It explores existing modeling techniques and optimization strategies to enhance the performance of microalgae-based systems, ultimately supporting the development of technology and sustainable practices by guiding upcoming R&D projects in this field.(

**Methods of Microalgae Biomass Production: Open vs. Closed Systems and Nutritional Approaches**

The production of microalgae biomass can be carried out using open or closed systems.( Khavari, F., Saidijam, M., Taheri, M., & Nouri, F. 2021). Most research has focused on using open pond-like systems, which are employed in large-scale microalgae growth due to their scalability, low power consumption, simple cleaning procedure, and inexpensive construction cost. Endres, C. H., Roth, A., & Brück, T. B. (2018). However, open systems may be limited by unfavorable climatic conditions and greenhouse gas emissions, which can affect the microalgae's ability to process CO2 and reduce biomass output.[55]

On the other hand, the closed system involves cultivating the algae in a closed photoreactor.(Pradhan, Debabrata, Lala Behari Sukla, 2015) This method reduces both the risk of contamination and the yield of microalgae biomass. It also supports the microalgae's capacity to transform CO2 into biomass.( Xu, Xianzhen, et al.2019) .

The production of microalgae biomass in both closed and open systems (Morales, M., Sánchez, L., & Revah, S. (2018) .depends on the method of nutrition.Autotrophic microalgae have distinct growth requirements compared to heterotrophic microalgae, while mixotrophic microalgae have varying growth conditions.( Kasiri, Sepideh, Ania Ulrich 2019). Nitrate, phosphate, and other necessary components are used in both open and closed systems to promote high biomass production. (Chen, Cheng, et al 2022)

Heterotrophic microalgae produce biomass using organic carbon substrates as a source of energy and carbon, independently of light.( Muylaert, Koenraad, et al.,( Muylaert, Koenraad, et al. 2015) (Pang, Na, et al 2019).They are often grown using glycerol, glucose, and acetate as carbon sources, but research has shown that wastewater can also be used as a source of organic carbon and energy.(Abreu, Ana P., et al 2015) Heterotrophic microalgae biomass production is popular on a commercial scale due to its high lipid buildup, making it suitable for biofuel generation.

In contrast, autotrophic microalgae produce biomass by using CO2 and water in sunlight, while mixotrophic microalgae use both organic and inorganic carbon sources.( Singh, J., & Saxena, R. C. 2015). The mixotrophic process produces microalgae biomass that accumulates more lipids, carbohydrates, proteins, and other biomolecules compared to biomass produced by either the heterotrophic or autotrophic methods.( García-Camacho, F., Sánchez-Mirón, A.,),( del Rio‐Chanona, E. A., Wagner,2019)

  Fig: different types of open ponds

 

Fig: a closed photobioreactor

 **Mathematical Modeling of Microalgae Growth Kinetics**

Different versions of microalgae models have been developed, incorporating key factors such as light, nutrients, CO2 sequestration, culture system, and microalgae biomass production(Almomani, F. 2020) . Droop introduced the initial model for microalgae growth kinetics in 1983. (Yuan, S., Lei, W., Liu, Q., Liu, R., Liu, J., Fu, J., & Han, Y. (2023) .This model illustrates the relationship between the growth process and the internal substrate of microalgae cells, as described by Equation (1) where μ represents the specific growth rate, μm denotes the theoretical growth rate at infinite quota, Kq is the minimum quota, and Q is the cell quota. After Droop's (1983) work, several studies focused on mathematical modeling and predicting biomass production. (Huesemann, Michael H., et al.2013)monitoring the exterior substrate is easier and more precise than monitoring internal cell quotas, even though most models employ the Monod formulation rather than the Droop model. These models were created using empirical data that showed a connection between microalgae growth and substrate concentration in the culture medium. In order to address the many reasons of differences in microalgae development, dynamic models have been developed.

µ= µ𝑚 S/ks +S(1)

µ= µ𝑚 S/ks +S +S^2/kl(2)

where μ is the specific growth rate, μm is the maximum growth rate , S is the substrate concentration, KS is the half substrate saturation constant,and kI is the inhibition parameter

 

Fig: Mechanism of biomass production by autotrophic microalgae

**Optimizing CO2 Fixation and Biomass Production in Microalgae Systems**

Microalgae play a crucial role in CO2 fixation by using CO2 to produce biomass, particularly lipids, which can be used for biofuel generation.( Barrantes, Maritza Guerrero,2022) To maximize their potential for CO2 fixation and biomass production, it is important to optimize the process under ideal conditions.( Hossain, SM Zakir, Nahid Sultana 2023) .Understanding the behavior of microalgae and identifying the optimal operating parameters can be achieved through modeling microalgae systems. One common application of this research is using microalgae to remove CO2 from power plant exhaust gases. However, it's important to note that flue gas contains other gases such as SO2 and NO2, which can vary based on the source being burned. To develop an accurate model for CO2 fixation during biomass production, it is essential for createing a kinetic model for microalgae's CO2 tolerance in the air, as well as a model for CO2 utilization from the flue gas.( Maltsev, Y., Maltseva,2021) The kinetics of CO2 absorption and its behavior in liquid phase under different pH levels are critical factors to consider for carbon sequestration. Additionally, the pH level significantly affects the rate of CO2 fixation by microalgae, as chemicals like SO2 and NO2 can aid in photosynthesis. Most microalgae species exhibit increased biomass production and CO2 consumption at pH levels between 6 and 11. The models used for forecasting CO2 fixation in microalgae, represented by equations (2) and (3), are the Monod model, which shows monotonic behavior, and the Haldane-like model, which shows non-monotonic behavior characterized by inhibition at high substrate concentrations.

**Understanding the Impact of Light Intensity on Microalgae Biomass Production and Photosynthesis**

AS microalgae can efficiently consume CO2 when exposed to increasing light levels, they can generate biomass even under low light settings.( Braun, J. C., & Colla, L. M. 2023) Light modeling may be used to show how light affects biomass production, as light is essential for microalgae photosynthesis.( Magalhães, Iara Barbosa, et al 2022). In a microalgal cell, the link between light intensity and photosynthesis is represented by the symbol Pl, where l stands for light intensity and P for photosynthesis. The light inhibition regime, the light saturation regime, and the light restriction regime are the three separate regimes that make up Pl.( Saide, Assunta, Kevin A. Martínez 2021) .

Photosynthesis in light-limited regimes often happens at a rate proportionate to the rate of light intensity because the number of protons gathered determines photosynthesis speed.( Huesemann, M., et al 2016) Since the saturation limits for the light intensity necessary for photosynthesis have been achieved, the rate of photosynthesis in microalgae culture is usually at its maximum in light-saturated conditions and is not impacted by light intensity.(2016) Bernard, Olivier, Francis Mairet, Because light intensity over an inhibitory threshold causes key proteins for photosynthesis to become inactive, the rate of photosynthesis in microalgae culture tends to decline as light intensity increases under light inhibition regimes.( Koller, M. 2015).

Although no single model can account for all Pl, research has compiled a variety of interesting models that show how light intensity affects the growth of microalgae biomass.( Weitere, Markus,2018) . Type I, Type II, and Type III models are the three groups into which the created kinetic models may be separated based on theoretical knowledge.( Pang, Na, et al.2019) 73] According to the type I model, every microalgae cell in a well-mixed culture receives the same amount of light intensity and, as a result, has the same average rate of photosynthesis.54] Still, empirical studies have demonstrated that these models' kinetic characteristics depend on operational conditions such system size, incoming light intensity, or cell concentration (Masojídek et al., 2021).( Ramanna, L., Rawat, I., & Bux, F. 2017), 15]

The impact of light gradients on the local rate of photosynthetic activity in microalgae is demonstrated using the type II model.(Dubinsky, Z., & Iluz, D. (2015)) It creates a biological model that describes how local light intensity affects the rate at which photosynthesis occurs locally. (Ezike, Ngozika Chinonyerem Okechukwu, et al.2024) 42]
Type III models show how the light history of an algal cell influences its rate of photosynthetic activity, accounting for the fact that microalgae experience variations in light intensity as they pass through the system over time.( Sommer, U. (1991) .Usually, to build these models, the light history of the microalgae cells is determined, and a dynamic biological model is used to calculate the rate of photosynthesis of each individual microalgae cell.,( Moreno-Garcia, L., et al. 2019) 75]

**Understanding Nutrient Modeling for Microalgae Growth and Biomass Production**

These nutrients are essential for the formation of biomass by microalgae (Delgadillo-Mirquez et al., 2016). (Echenique-Subiabre, I., Greene, 2023) Microalgae's biomass output is sitively correlated with the concentration of nutrients, particularly phosphorus and nitrogen, which are necessary for microalgae to reach their maximum biomass productivity (Yaakob et al., 2021). (Dalsgaard, T. 2003). Nitrogen and phosphorus concentrations are often the focus of nutrient modeling in microalgae systems (Yaakob et al., 2021). The model used in the modeling and prediction of nitrogen and phosphorus in the system is shown in equations (4–7) below.( Perin, G., Bellan, A.,2019)

Nitrogen models:

μₘcₐ = μₘ (1 − qₙₓᵐⁱⁿ / qₙₓ)

where:

μₘ — max specific growth rate.

qₙₓ — internal nitrogen cell quota.

qₙₓᵐⁱⁿ — min nitrogen cell quota.

μₘcₐ = μₘ Sₙ / (Kₛₙ + Sₙ)

where:

μₘ — max specific growth rate.

Sₙ — nitrogen concentration.

Kₛₙ — half-saturation constant for nitrogen.

Phosphorus model:

μₘcₐ = μₘ Sₚ / (Kₛₚ + Sₚ)

where:

μₘ — max specific growth rate.

Sₚ — phosphorus concentration.

Kₛₚ — half-saturation constant phosphorus.

μₘcₐ = μₘ (1 − qₚₓᵐⁱⁿ / qₚₓ)

where:

μₘ — max specific growth rate.

qₚₓ — internal phosphorus cell quota.

qₚₓᵐⁱⁿ — min phosphorus cell quota.

**Factors to Consider for Modeling Photobioreactors for Microalgae Biomass Production**

It's crucial to predict photobioreactor behavior while doing research on the large-scale generation of microalgae biomass.( Zhao, B., Zhang, Y., Xiong, K., Zhang, Z., Hao, X., & Liu, T. 2011). Time and money will be saved as a result of optimizing the production of microalgae biomass.(Since temperature and light are two factors that directly affect an algae's capacity to create biomass, photobioreactors are essential to the generation of microalgae biomass.( Mimouni,Virginie The latitude and orientation of the photobioreactor, variations in light intensity due to seasonal changes, the influence of nearby objects casting shadows, the reflective qualities of the photobioreactor's surfaces, the absorption of light by microalgae affecting light distribution within the photobioreactor, the specific species of microalgae being used, and the impact of light gradients on microalgae growth and dark respiration.( Shriwastav, Amritanshu, JeenThomas 2017) .should all be taken into account when modeling photobioreactors for sustainable microalgae biomass production.

**Conclusion**

Utilizing microalgae biomass as a resource will help meet current demands without depleting resources needed for future generations.( Shadi W. Hassan, and Fawzi Banat 2022).It is a crucial component in manufacturing pharmaceuticals, biomedical instruments, biofuels, nutritional supplements, and aquaculture feeds.( Kasiri, Sepideh, Ania Ulrich 2016) .Additionally, it is commonly used in phycoremediation of contaminated water.

The long-term sustainability of freshwater and marine habitats is impacted by the disruption of the food chain caused by the production of aquaculture feeds from forage fish. The use of terrestrial plants as aquaculture feed is associated with overuse of freshwater resources and deforestation. As a result, vital food supplies including soybeans, maize, cottonseed, peas, wheat, and barley become scarce. Microalgae are a superior choice for producing feed for aquaculture because they yield higher net biomass than terrestrial plants. (Bose, A., Lin, R., Rajendran 2016) They do not generally require freshwater for growth, and they grow faster in wastewater.

Microalgae biomass is considered an efficient resource for aquaculture feed production due to its metabolic characteristics. Analyzing the effectiveness of microalgae biomass in aquaculture feed production has been published. The use of biofuel is increasing as a potential replacement for fossil fuels due to concerns about high costs and environmental impact. Switching to biofuels is seen as a way to reduce the strain of using over 86 million barrels of crude oil daily and mitigate the financial impact of rising crude oil prices. Fossil fuel usage contributes to over 25% of CO2 emissions, and using biofuels would provide environmental benefits.

The increased use of terrestrial plants for biofuel production has led to rising food crop prices and increased deforestation, raising concerns about the significance of biofuels.( Rehman, M., Kesharvani, S., Dwivedi, G., & Suneja, K. G. 2022) This could also increase greenhouse gas emissions rather than decrease them. The main points of contention in the discussion about the viability of biofuels are fuel vs. food, greenhouse gas emissions, and ecosystem services.( Amaro, Helena M., 2012) The issues related to using food crops for biofuels can be addressed by utilizing microalgae biomass, as they develop more quickly and are more efficient at producing biofuel compared to terrestrial plants. Microalgae can store more lipids in their biomass and sequester inorganic carbon, addressing concerns related to greenhouse gas emissions and ecosystem services.( Huesemann, Michael H., et al 2013

**Reference:**

1. Abreu, Ana P., et al. "A comparison between microalgal autotrophic growth and metabolite accumulation with heterotrophic, mixotrophic and photoheterotrophic cultivation modes." *Renewable and Sustainable Energy Reviews* 159 (2022): 112247.
2. Abu-Ghosh, S., Fixler, D., Dubinsky, Z., & Iluz, D. (2015). Continuous background light significantly increases flashing-light enhancement of photosynthesis and growth of microalgae. *Bioresource technology*, *187*, 144-148.
3. Ahmad, Ashfaq, Shadi W. Hassan, and Fawzi Banat. "An overview of microalgae biomass as a sustainable aquaculture feed ingredient: Food security and circular economy." *Bioengineered* 13.4 (2022): 9521-9547.
4. Ahmad, I., A. Yuzir, S. E. Mohamad, K. Iwamoto, and N. Abdullah. "Role of
5. *Materials Science and Engineering*, vol. 1051, no. 1, p. 012059. IOP Publishing, 2021.
6. AlMallahi, Maryam Nooman, Sara Maen Asaad, Abrar Inayat, K. Harby, and Mahmoud Elgendi. "Analysis of solar-powered adsorption desalination systems: current research trends, developments, and future perspectives." *International Journal of Thermofluids* (2023): 100457.
7. Almomani, F. (2020). Kinetic modeling of microalgae growth and CO2 bio-fixation using central composite design statistical approach. *Science of the Total Environment*, *720*, 137594.
8. Amaro, H. M., Macedo, Â. C., & Malcata, F. X. (2012). Microalgae: an alternative as sustainable source of biofuels?. *Energy*, *44*(1), 158-166.
9. Amaro, Helena M., Ângela C. Macedo, and F. Xavier Malcata. "Microalgae: an alternative as sustainable source of biofuels?." *Energy* 44.1 (2012): 158-166.
10. Ansari, Faiz Ahmad, et al. "Improving the feasibility of aquaculture feed by using microalgae." *Environmental Science and Pollution Research* 28.32 (2021): 43234-43257.
11. Barrantes, Maritza Guerrero, Olman Gómez Espinoza, and Kattia Núñez Montero. "Microalgae-based approaches to overcome the effects of the COVID-19 pandemic." *Tecnología en Marcha* 35, no. 1 (2022): 84-93.
12. Bazdar, Elahe, et al. "The effect of different light intensities and light/dark regimes on the performance of photosynthetic microalgae microbial fuel cell." *Bioresource technology* 261 (2018): 350-360.
13. Benedetti, M., Vecchi, V., Barera, S. and Dall’Osto, L., 2018. Biomass from microalgae: the potential of domestication towards sustainable biofactories. *Microbial Cell Factories*, *17*, pp.1-18.
14. Bernard, Olivier, Francis Mairet, and Benoît Chachuat. "Modelling of microalgae culture systems with applications to control and optimization." *Microalgae Biotechnology* (2016): 59-87.
15. Bernardi, A., Nikolaou, A., Meneghesso, A., Morosinotto, T., Chachuat, B., & Bezzo, F. (2016). High-fidelity modelling methodology of light-limited photosynthetic production in microalgae. *PloS one*, *11*(4), e0152387.
16. Bose, A., Lin, R., Rajendran, K., O'Shea, R., Xia, A., & Murphy, J. D. (2019). How to optimise photosynthetic biogas upgrading: a perspective on system design and microalgae selection. *Biotechnology advances*, *37*(8), 107444.
17. Bradley, T., Rajaeifar, M. A., Kenny, A., Hainsworth, C., del Pino, V., del Valle Inclán, Y., ... & Heidrich, O. (2023). Life cycle assessment of microalgae-derived biodiesel. *The International Journal of Life Cycle Assessment*, *28*(5), 590-609.
18. Braun, J. C., & Colla, L. M. (2023). Use of Microalgae for the Development of Biofertilizers and Biostimulants. *BioEnergy Research*, *16*(1), 289-310.
19. Brindley, Celeste, et al. "Light regime optimization in photobioreactors using a dynamic photosynthesis model." *Algal Research* 16 (2016): 399-408.
20. Cezare-Gomes, E.A., Mejia-da-Silva, L.D.C., Pérez-Mora, L.S., Matsudo, M.C., Ferreira-Camargo, L.S., Singh, A.K. and de Carvalho, J.C.M., 2019. Potential of microalgae carotenoids for industrial application. *Applied biochemistry and biotechnology*, *188*, pp.602-634.
21. Chen, Cheng, et al. "The potential and challenge of microalgae as promising future food sources." *Trends in Food Science & Technology* 126 (2022): 99-112.
22. Chiranjeevi, P., & Venkata Mohan, S. (2016). Optimizing the critical factors for lipid productivity during stress phased heterotrophic microalgae cultivation. *Frontiers in Energy Research*, *4*, 26.
23. Choi, Hong Il, Young Joon Sung, Min Eui Hong, Jonghee Han, Byoung Koun Min, and Sang Jun Sim. "Reconsidering the potential of direct microalgal biomass utilization as end-products: A review." *Renewable and Sustainable Energy Reviews* 155 (2022): 111930
24. Costa, Jorge Alberto Vieira, et al. "Open pond systems for microalgal culture." *Biofuels from algae*. Elsevier, 2019. 199-223.
25. Costa, Jorge Alberto Vieira, et al. "Potential of microalgae as biopesticides to contribute to sustainable agriculture and environmental development." *Journal of Environmental Science and Health, Part B* 54.5 (2019): 366-375.
26. Dalsgaard, T. (2003). Benthic primary production and nutrient cycling in sediments with benthic microalgae and transient accumulation of macroalgae. *Limnology and Oceanography*, *48*(6), 2138-2150.
27. De Andrade, G. A., Berenguel, M., Guzmán, J. L., Pagano, D. J., & Acién, F. G. (2016). Optimization of biomass production in outdoor tubular photobioreactors. *Journal of Process Control*, *37*, 58-69.
28. de Jesus Raposo, Maria Filomena, and Alcina Maria Miranda Bernardo de Morais. "Microalgae for the prevention of cardiovascular disease and stroke." *Life sciences* 125 (2015): 32-41.
29. de Oliveira Prado, L., Bolzani, H. R., de Simone Souza, H. H., Ruas, G., & da Silva, G. H. R. (2023). Microalgal cultivation in open and closed systems under a tropical climate: A life cycle comparison. *Journal of Cleaner Production*, *422*, 138631.
30. de Oliveira Prado, Larissa, et al. "Microalgal cultivation in open and closed systems under a tropical climate: A life cycle comparison." *Journal of Cleaner Production* 422 (2023): 138631.
31. del Rio‐Chanona, E. A., Wagner, J. L., Ali, H., Fiorelli, F., Zhang, D., & Hellgardt, K. (2019). Deep learning‐based surrogate modeling and optimization for microalgal biofuel production and photobioreactor design. *AIChE Journal*, *65*(3), 915-923.
32. del Rio‐Chanona, Ehecatl A., et al. "Dynamic modeling of green algae cultivation in a photobioreactor for sustainable biodiesel production." *Biotechnology and bioengineering* 115.2 (2018): 359-370.
33. Echenique-Subiabre, I., Greene, J. M., Ryan, A., Martinez, H., Balleza, M., Gerber, J., ... & Shurin, J. B. (2023). Site-specific factors override local climatic conditions in determining microalgae productivity in open raceway ponds. *Algal Research*, *74*, 103235.
34. Endres, C. H., Roth, A., & Brück, T. B. (2018). Modeling microalgae productivity in industrial-scale vertical flat panel photobioreactors. *Environmental science & technology*, *52*(9), 5490-5498.
35. Ezike, Ngozika Chinonyerem Okechukwu, et al. "Bioethanol Revolution: Unveiling the Advancement and Emerging Trends in Production of Sustainable Energy Production." (2024).
36. García-Camacho, F., Sánchez-Mirón, A., Molina-Grima, E., Camacho-Rubio, F., & Merchuck, J. C. (2012). A mechanistic model of photosynthesis in microalgae including photoacclimation dynamics. *Journal of theoretical biology*, *304*, 1-15.
37. Gonçalves, A. L., Simões, M., & Pires, J. C. M. (2014). The effect of light supply on microalgal growth, CO2 uptake and nutrient removal from wastewater. *Energy Conversion and Management*, *85*, 530-536.
38. Gonçalves, J., Freitas, J., Fernandes, I., & Silva, P. (2023). Microalgae as biofertilizers: a sustainable way to improve soil fertility and plant growth. *Sustainability*, *15*(16), 12413.
39. Goswami, R. K., Mehariya, S., Verma, P., Lavecchia, R., & Zuorro, A. (2021). Microalgae-based biorefineries for sustainable resource recovery from wastewater. *Journal of Water ProcessEngineering*, *40*, 101747.
40. Hossain, S. Z., Sultana, N., Razzak, S. A., & Hossain, M. M. (2022). Modeling and multi-objective optimization of microalgae biomass production and CO2 biofixation using hybrid intelligence approaches. *Renewable and Sustainable Energy Reviews*, *157*, 112016.
41. Hossain, SM Zakir, Nahid Sultana, M. Ezzudin Mohammed, Shaikh A. Razzak, and Mohammad M. Hossain. "Hybrid support vector regression and crow search algorithm for modeling and multiobjective optimization of microalgae-based wastewater treatment." *Journal of Environmental Management* 301 (2022): 113783.
42. Huesemann, M., Crowe, B., Waller, P., Chavis, A., Hobbs, S., Edmundson, S., & Wigmosta, M. (2016). A validated model to predict microalgae growth in outdoor pond cultures subjected to fluctuating light intensities and water temperatures. *Algal Research*, *13*, 195-206.
43. Huesemann, M., et al. "A validated model to predict microalgae growth in outdoor pond cultures subjected to fluctuating light intensities and water temperatures." *Algal Research* 13 (2016): 195-206.
44. Huesemann, Michael H., et al. "A screening model to predict microalgae biomass growth in photobioreactors and raceway ponds." *Biotechnology and bioengineering* 110.6 (2013): 1583-1594.
45. Hunsberger, C., Bolwig, S., Corbera, E., & Creutzig, F. (2014). Livelihood impacts of biofuel crop production: Implications for governance. *Geoforum*, *54*, 248-260.
46. Kasiri, Sepideh, Ania Ulrich, and Vinay Prasad. "Kinetic modeling and optimization of carbon dioxide fixation using microalgae cultivated in oil-sands process water." *Chemical Engineering Science* 137 (2015): 697-711.
47. Kasiri, Sepideh, Ania Ulrich Microalgae based biofuel: challenges and opportunities. *Biofuels: Technology, Challenges and Prospects*, 157-175.
48. Khalid, Azianabiha A. Halip, et al. "Assessing the feasibility of microalgae cultivation in agricultural wastewater: The nutrient characteristics." *Environmental Technology & Innovation* 15 (2019): 100402.
49. Khan, Muhammad Imran, Jin Hyuk Shin, and Jong Deog Kim. "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 (2018): 1-21.
50. Khavari, F., Saidijam, M., Taheri, M., & Nouri, F. (2021). Microalgae: therapeutic potentials and applications. *Molecular biology reports*, *48*(5), 4757-4765.
51. Koller, M. (2015). Design of closed photobioreactors for algal cultivation. *Algal Biorefineries: Volume 2: Products and Refinery Design*, 133-186.
52. Lehmuskero, Anni, Matilde Skogen Chauton, and Tobias Boström. "Light and photosynthetic microalgae: cellular-and molecular-scale optical processes." *Progress in oceanography* 168 (2018): 43-56..
53. Li, Shengnan, Xue Li, and Shih-Hsin Ho. "Microalgae as a solution of third world energy crisis for biofuels production from wastewater toward carbon neutrality." *Chemosphere* 291 (2022): 132863.
54. Llamas, B., Suárez-Rodríguez, M. C., González-López, C. V., Mora, P., & Acién, F. G. (2021). Techno-economic analysis of microalgae related processes for CO2 bio-fixation. *Algal Research*, *57*, 102339.
55. López Muñoz, Ignacio, and Olivier Bernard. "Modeling the influence of temperature, light intensity and oxygen concentration on microalgal growth rate." *Processes* 9.3 (2021): 496.
56. Magalhães, Iara Barbosa, et al. "Agro-industrial wastewater-grown microalgae: A techno-environmental assessment of open and closed systems." *Science of The Total Environment* 834 (2022): 155282.
57. Maltsev, Y., Maltseva, K., Kulikovskiy, M., & Maltseva, S. (2021). Influence of light conditions on microalgae growth and content of lipids, carotenoids, and fatty acid composition. *Biology*, *10*(10), 1060.
58. Maltsev, Yevhen, et al. "Influence of light conditions on microalgae growth and content of lipids, carotenoids, and fatty acid composition." *Biology* 10.10 (2021): 1060
59. Meenatchisundaram, Karthikeyan, et al. "Data-driven model development for prediction and optimization of biomass yield of microalgae-based wastewater treatment." *Sustainable Energy Technologies and Assessments* 63 (2024): 103670.
60. Mimouni, Virginie, Lionel Ulmann, Virginie Pasquet, Marie Mathieu, Laurent Picot, Gaël Bougaran, Jean-Paul Cadoret, Annick Morant-Manceau, and Benoît Schoefs. "The potential of microalgae for the production of bioactive molecules of pharmaceutical interest." *Current pharmaceutical biotechnology* 13, no. 15 (2012): 2733-2750.
61. Morales, M., Sánchez, L., & Revah, S. (2018). The impact of environmental factors on carbon dioxide fixation by microalgae. *FEMS microbiology letters*, *365*(3), fnx262.
62. 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.
63. Moreno-Garcia, L., et al. "Effect of environmental factors on the biomass and lipid production of microalgae grown in wastewaters." *Algal Research* 41 (2019): 101521.
64. Muylaert, Koenraad, et al. "Wastewater as a source of nutrients for microalgae biomass production." *Biomass and Biofuels from Microalgae: Advances in Engineering and Biology* (2015): 75-94.
65. Pang, Na, et al. "Exploiting mixotrophy for improving productivities of biomass and co-products of microalgae." *Renewable and Sustainable Energy Reviews* 112 (2019): 450-460.
66. Pang, Na, et al. "Exploiting mixotrophy for improving productivities of biomass and co-products of microalgae." *Renewable and Sustainable Energy Reviews* 112 (2019): 450-460.
67. Perin, G., Bellan, A., Bernardi, A., Bezzo, F., & Morosinotto, T. (2019). The potential of quantitative models to improve microalgae photosynthetic efficiency. *Physiologia plantarum*, *166*(1), 380-391.
68. Peter, A. P., Koyande, A. K., Chew, K. W., Ho, S. H., Chen, W. H., Chang, J. S., ... & Show, P. L. (2022). Continuous cultivation of microalgae in photobioreactors as a source of renewable energy: Current status and future challenges. *Renewable and Sustainable Energy Reviews*, *154*, 111852.
69. Pradhan, Debabrata, Lala Behari Sukla, and Roberto Acevedo. "Microalgae for future biotechnology industries." *Inglomayor* 13 (2017): 40-55.
70. Raja, R., et al. "Biomass from microalgae: an overview." *Oceanography* 2.1 (2014): 1-7.
71. Ramanna, L., Rawat, I., & Bux, F. (2017). Light enhancement strategies improve microalgal biomass productivity. *Renewable and Sustainable Energy Reviews*, *80*, 765-773.
72. Ramanna, Luveshan, Ismail Rawat, and Faizal Bux. "Light enhancement strategies improve microalgal biomass productivity." *Renewable and Sustainable Energy Reviews* 80 (2017): 765-773.
73. Razzak, Shaikh A., Mohammad M. Hossain, Rahima A. Lucky, Amarjeet S. Bassi, and Hugo De Lasa. "Integrated CO2 capture, wastewater treatment and biofuel production by microalgae culturing—a review." *Renewable and sustainable energy reviews* 27 (2013): 622-653.
74. Rehman, M., Kesharvani, S., Dwivedi, G., & Suneja, K. G. (2022). Impact of cultivation conditions on microalgae biomass productivity and lipid content. *Materials Today: Proceedings*, *56*, 282-290.
75. Rodionova, Margarita V., et al. "Biofuel production: challenges and opportunities." *International Journal of Hydrogen Energy* 42.12 (2017): 8450-8461.
76. Romagnoli, F., Weerasuriya-Arachchige, A. R. P. P., Paoli, R., Feofilovs, M., & Ievina, B. (2021). Growth kinetic model for microalgae cultivation in open raceway ponds: a system dynamics tool. *Rigas Tehniskas Universitates Zinatniskie Raksti*, *25*(1), 1317-1336.
77. Russell, Callum, Cristina Rodriguez, and Mohammed Yaseen. "High-value biochemical products & applications of freshwater eukaryotic microalgae." *Science of The Total Environment* 809 (2022): 151111.
78. Saide, Assunta, Kevin A. Martínez, Adrianna Ianora, and Chiara Lauritano. "Unlocking the health potential of microalgae as sustainable sources of bioactive compounds." *International Journal of Molecular Sciences* 22, no. 9 (2021): 4383.
79. Sforza, E., Pastore, M., Franke, S. M., & Barbera, E. (2020). Modeling the oxygen inhibition in microalgae: An experimental approach based on photorespirometry. *New biotechnology*, *59*, 26-32.
80. Shitanaka, T., Fujioka, H., Khan, M., Kaur, M., Du, Z. Y., & Khanal, S. K. (2023). Recent advances in microalgal production, harvesting, prediction, optimization, and control strategies. *Bioresource Technology*, 129924.
81. Shitanaka, Ty, et al. "Recent advances in microalgal production, harvesting, prediction, optimization, and control strategies." *Bioresource Technology* (2023): 129924.
82. Shriwastav, Amritanshu, Jeenu Thomas, and Purnendu Bose. "A comprehensive mechanistic model for simulating algal growth dynamics in photobioreactors." *Bioresource technology* 233 (2017): 7-14
83. Siddiki, S. Y. A., Mofijur, M., Kumar, P. S., Ahmed, S. F., Inayat, A., Kusumo, F., ... & Mahlia, T. M. I. (2022). Microalgae biomass as a sustainable source for biofuel, biochemical and biobased value-added products: An integrated biorefinery concept. *Fuel*, *307*, 121782.
84. Singh, J., & Saxena, R. C. (2015). An introduction to microalgae: diversity and significance. In *Handbook of marine microalgae* (pp. 11-24). Academic Press.
85. Sommer, U. (1991). A comparison of the Droop and the Monod models of nutrient limited growth applied to natural populations of phytoplankton. *Functional Ecology*, 535-544.
86. Verma, R., Kumari, K. K., Srivastava, A., & Kumar, A. (2020). Photoautotrophic, mixotrophic, and heterotrophic culture media optimization for enhanced microalgae production. *Journal of Environmental Chemical Engineering*, *8*(5), 104149.
87. Wang, Shi‐Kai, Amanda R. Stiles, Chen Guo, and Chun‐Zhao Liu. "Microalgae cultivation in photobioreactors: An overview of light characteristics." *Engineering in Life Sciences* 14, no. 6 (2014): 550-559.
88. Weitere, Markus, Martina Erken, Nabil Majdi, Hartmut Arndt, Helge Norf, Michael Reinshagen, Walter Traunspurger, Anja Walterscheid, and Jennifer K. Wey. "The food web perspective on aquatic biofilms." *Ecological Monographs* 88, no. 4 (2018): 543-559.
89. Xu, Xianzhen, et al. "Progress, challenges and solutions of research on photosynthetic carbon sequestration efficiency of microalgae." *Renewable and Sustainable Energy Reviews* 110 (2019): 65-82.
90. Yaakob, Maizatul Azrina, et al. "Influence of nitrogen and phosphorus on microalgal growth, biomass, lipid, and fatty acid production: an overview." *Cells* 10.2 (2021): 393.
91. Yuan, S., Lei, W., Liu, Q., Liu, R., Liu, J., Fu, J., & Han, Y. (2023). Distribution and environmental impact of microalgae production potential under the carbon-neutral target. *Energy*, *263*, 125584.
92. Zhao, B., Zhang, Y., Xiong, K., Zhang, Z., Hao, X., & Liu, T. (2011). Effect of cultivation mode on microalgal growth and CO2 fixation. *Chemical engineering research and design*, *89*(9), 1758-1762.
93. Zhuang, L. L., Yu, D., Zhang, J., Liu, F. F., Wu, Y. H., Zhang, T. Y., ... & Hu, H. Y. (2018). The characteristics and influencing factors of the attached microalgae cultivation: a review. *Renewable and Sustainable Energy Reviews*, *94*, 1110-1119.