Microalgae Cultivated under Magnetic Field Action

Subjects: Plant Sciences

Contributor: Kricelle Mosquera Deamici , Katarzyna Dziergowska , Pedro Garcia Pereira Silva , Izabela Michalak , Lucielen Oliveira Santos , Jerzy Detyna , Sunita Kataria , Marian Brestic , Mohammad Sarraf , Monirul Islam

Microalgae and cyanobacteria include procaryotic and eucaryotic photosynthetic micro-organisms that produce biomass rich in biomolecules with a high value. Some examples of these biomolecules are proteins, lipids, carbohydrates, pigments, antioxidants, and vitamins. Microalgae are also considered a good source of biofuel feedstock. The microalga-based biorefinery approach should be used to promote the sustainability of biomass generation since microalga biomass production can be performed and integrated into a circular bioeconomy structure. To include an environmentally sustainable approach with microalga cultures, it is necessary to develop alternative ways to produce biomass at a low cost, reducing pollution and improving biomass development. Different strategies are being used to achieve more productivity in cultivation, such as magnets in cultures. Magnetic forces can alter microalga metabolism, and this field of study is promising and innovative, remains an unexplored area.

microalgae | magnetic field | growth rate | chemical composition | algal biorefinery | environmental safety

1. Introduction

The microalga biorefinery concept assumes the conversion of biomass into marketable chemicals, such as biofuels as other high-value co-products [1]. Microalga biomass is an interesting feedstock for biorefineries due to its chemical composition, fast growth, ability to grow in low-quality water and, additionally, remove contaminants from wastewater, as well as capture and recycle carbon dioxide (CO_2) from industrial flue emissions [2]. The impacts to the environment caused by greenhouse gas emissions are improving the forces to generate energy from renewable sources. Among the green raw materials that can be used to create biofuels, microalgae are considered an alternative to replace fossil fuels by playing an important role in global environmental issues, leading to a sustainable path to obtaining biofuels [3]. In order to further enhance alga growth and synthesis of biologically active compounds of commercial interest, electromagnetic biostimulation of living cultures has been proposed [2]. Magnetic fields (MFs), used as a physical treatment, have been gaining more popularity in microalga cultivation, since they are non-toxic and non-polluting, without secondary contamination. Furthermore, no external energy is required for MF treatment. As a result, this saves energy and protects the environment [4][5][6][7].

Exposure of algae to the MF action increases not only biomass production, but also its composition—the content of carbohydrates, essential amino acids, lipids, pigments (e.g., phycocyanin), and antioxidants, which guarantees interest in the food, cosmetics, and feed industries, e.g., [8][9][10][11][12][13][14][15][16][17]. MF-stimulated microalga cultivation with enhanced lipid content may be beneficial in biodiesel production; however, its manufacturing costs are still significantly higher than fossil diesel, e.g., [5][10][18]. Besides biodiesel, microalgae can constitute the raw material for bioethanol production via fermentation processes, biogas generated during anaerobic decomposition of biomass, or hydrogen produced by photobiological processes [19].

The use of wastewater, rich in phosphorus and nitrogen, as the growth medium for microalgae grown under MF exposure seems to be justified and beneficial for the environment [5][20]. Microalgae treated with MFs may eliminate from wastewater not only inorganic, but also organic pollutants—e.g., starch [20] or dyes [21]. In this process, after wastewater treatment, biomass may be used for biofuel production, e.g., [4][5]. Exposure to MFs may also increase CO_2 biofixation by microalgae, since they are able to use atmospheric CO_2 (from industrial flue gases) as a carbon source to produce valuable compounds, while reducing the negative impact on the environment of this greenhouse gas [17].

In order to achieve satisfactory results in biorefineries using microalga biomass exposed to MFs as a feedstock, the optimization of this process is necessary, as well as conducting detailed research in real conditions, not only indoors cultivation, but also outdoors in open-raceway ponds. The biological consequences of magnetic exposure in microalgae are dependent on the magnetic intensity, frequency, and exposure period [6][9].

2. Microalga Cultures and Magnetic Fields

Microalgae and cyanobacteria (blue algae) are photosynthetic microorganisms, being found in different ecosystems (aquatic and terrestrial), which generate biomass using different nutrient sources, CO_2, and illuminance. These microorganisms represent a wide variety of species that may survive in an extensive variety of environmental conditions [22][23]. In general, these microorganisms develop with a relatively fast growth rate and simple nutritional requirements. Furthermore, they may be phylogenetically classified as prokaryotic or eukaryotic and are considered favorable for biomass and different biomolecules' production, such as proteins, carbohydrates, and lipids [24][25].

In this context, microalgae may produce biomass by three specific systems: photoautotrophic, heterotrophic, and mixotrophic cultivation [26]. Photoautotrophic cultivation is the most-common system to produce biomass and uses solar illuminance and CO_2 as an energy source. Thus, it is important to highlight the high photosynthetic efficiency of these microorganisms, capable of capturing CO_2 from the environment and using it for their growth [27][28].

In mixotrophic cultures (a variant of heterotrophic system), organic compounds and CO_2 are assimilated by photosynthetic and respiratory metabolism to develop a rapid growth rate and biomass productivity. In this system, organic carbon sources are added, such as simple or complex sugars and glycerol. The ability to easily assimilate available carbon in the medium may promote the accumulation of some specific macromolecules, such as lipids and carbohydrates [27][29].

The production of metabolites of interest by these microorganisms is determined by different widely studied key factors, such as nutrient composition, illuminance, temperature, pH, CO_2 concentration, and agitation/aeration [22][30][31]. Thus, the microalgal biomass produced may be destined for different applications (**Figure 1**), including for use in industrial processes [14][27], but this also needs to be highlighted as a potential resource for biofuel production [23][31].

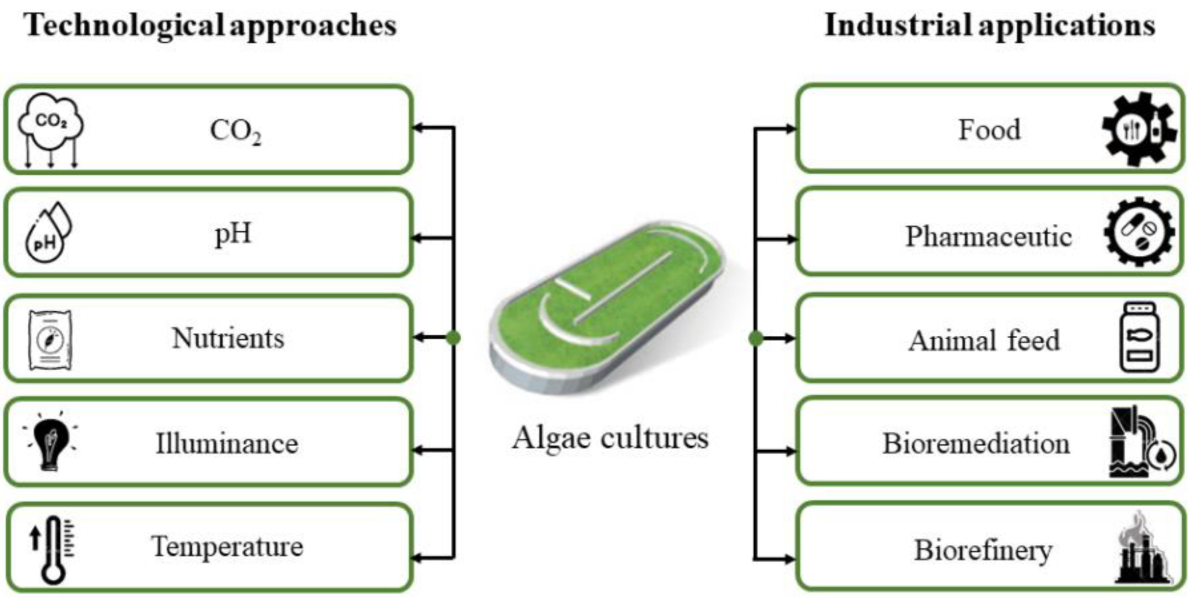

Figure 1. Factors influencing algae cultures and possibilities for industrial applications of microalga biomass.

Several technological approaches have been used in microalga cultures to increase biomass yield [27][32]. However, new strategies have been studied to induce physical or chemical stress during cultivation. They can be applied individually or synergistically, activating cellular defense mechanism by these microorganisms, mainly stimulating carbohydrate and lipid production, essential macromolecules for the use in biorefineries [23].

Regarding these new strategies that have been employed in microalga cultivation, MF application has been shown to be an alternative technological approach, due to its interaction with biological systems, positively influencing the production of biomass and compounds of interest [6][15].

This technological approach has been used in bioprocesses interacting with cell microorganisms to improve some compounds of interest, such as biomass and ethanol by *Saccharomyces cerevisiae* [33][34], glutathione by *S. cerevisiae* [35], biomass and carotenoids by *Phaffia rhodozyma* [36], laccase by *Candida tropicalis* [37], red and yellow pigment by *Monascus purpureus* [38], citric acid and cellulase by *Aspergillus niger* [39], inulinase production by *Geotrichum candidum* [40], lipid and pigments by *Chlorella kessleri* [8], protein and phycocyanin by *Spirulina* sp. LEB 18 [13], carbohydrate by *Chlorella minutissima* [41], and biomass and lipid content by *Chlorella homosphaera* [10].

3. Microalga-Based Biorefinery

The term biorefinery is well known as an industrial plant where crude oil is converted into useful oil products, such as petroleum, gasoline, and fuel oils, among others. The concept includes the process of obtaining energy and high-value products through biomass transformation in a sustainable way [3]. The term microalga-based biorefinery is similar, where microalga biomass is transformed into high-value-added bioproducts, such as biofuels (biodiesel, bioethanol, biogas, biohydrogen), bioplastics, pigments, nutraceuticals, and biofertilizers [42][43]. The microalga-based biorefinery may be viable, since these microorganisms are a biofuel feedstock, besides being able to capture atmospheric CO_2 and produce biomass rich in many bioproducts, through wastewater bioremediation [44].

Microalga cultivation has many advantages that make this type of biorefinery feasible. These microorganisms may be cultivated under sunlight and atmospheric CO_2, if they can use it as a carbon source, minimizing cultivation costs. Besides, the microalga culture does not require arable land and dependence on seasonality. Microalgae grow photosynthetically, depending only on sunlight, CO_2, and nutrients from the culture medium.

The biorefinery concept was created to describe the biofuels and high-value biomolecules' production from biomass by the integration of bioprocessing with a low environmental impact at a sustainable cost. The microalga-based biorefinery fits this concept, since it is possible to produce biofuels from biomass rich in lipids and carbohydrates, in outdoors conditions with alternative culture media, which is a way to reduce production and energy costs. The biorefinery is a design for sustainable waste reuse and energy production. A microalga-based biorefinery is shown in **Figure 2**.

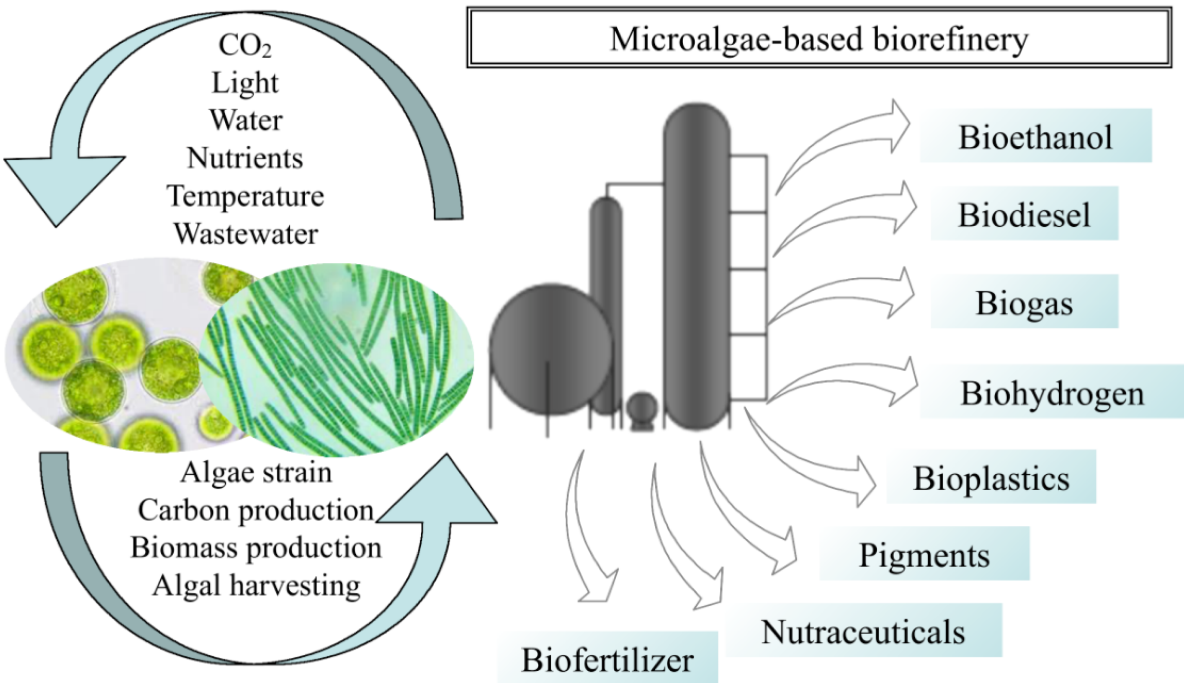

Figure 2. General scheme of microalga-based biorefinery.

Microalga biorefineries are developed with the aim to reduce biomolecules' production costs. For this purpose, the implementation of an integrated production process is necessary to achieve its sustainability, aiming at waste reduction and efficient transformation of biomass into energy, polymers, and food supplements. The integration of CO_2 mitigation and biofuel production, named CO_2-neutral fuels, has been used in the biorefinery approach. This environmental challenge is one of the most urgent in the world, given the huge gaseous emissions and their consequential climatic changes and warming effects [45].

High-value co-products and cultivation strategies must be used for a microalga-based biorefineries to be economically viable. The most-promising strategies involve microalga cultivation under atmospheric CO_2 mitigation, the use of wastewater as a substitute for culture media, and finally, the extraction of bioproducts from microalga biomass, as the feedstock for biofuel production [46]. Besides, MF strategies during microalga cultivation can be considered an important ally in the biorefinery approach, since this could enhance the biomass and compound production [11].

4. Sustainable and Environmentally Friendly Application of Microalgae

Microalgae present a high potential to produce many green chemicals, as already shown here, and because of that, these microorganisms may be treated as a "living biorefinery", considering that, while converting CO_2 and water to O_2, it is also possible to produce a rich biomass. Microalgae are represented as a sustainable and environmentally friendly raw material, since microalgal biomass may be obtained with low energy and costs with a good strategy. There are many ways to demonstrate that microalga biomass and cultivations may be applied as a sustainable and environmentally friendly utilization such as nutraceutics, food industry, and animal feed [3].

These microorganisms can grow with sunlight and use wastewater to "feed" themselves, such that this could be a more environmentally friendly way to obtain the biomass, since, as presented before, the microalgae can use the wastewater from different sources to replace the culture medium, besides performing wastewater treatment. In addition, microalgal biomass can be obtained year-round, unlike other crops, which can only be cultivated in particular periods [17]. This fact is important because we do not need to wait until the right season, nor do they require arable land, being an independent culture that would not affect the human food chain.

On the other side, to match the rising food demand, agrochemicals', such as pesticides/fertilizers, utilization on agricultural crops is currently increasing. Microalgae can also solve a part of this problem, because they can act as microbial biopesticides [47]. Biofertilizers can be used as nitrogen fixators, phosphates, and potassium-solubilizing biofertilizers, biofertilizers for secondary macronutrients such as iron and zinc, and phosphorus-mobilizing biofertilizers [48]. Microalgae have the ability to inhibit several pathogens contaminating plant cultures [47][49] due to the different compounds (phenolic compounds and terpenes) present in the biomass, acting as growth regulators against pathogens [50][51].

The biofuel from microalga biomass is known as the third generation of biofuels that has been emerging in the world [43]. It is expected that this class of biofuels will minimize the dependency on fossil fuels, including the environmental issues related to their use, such as pollution and the increase in the greenhouse effect. Among the diverse sources for this generation of biofuels, microalga biomass presents a high potential to replace fossil fuels, being a renewable, nontoxic, and eco-friendly source. The oils present in microalga biomass have similar properties as vegetable oils. According to the Global Market Insight (GMI) report, alga-based biofuels may substitute petroleum-based fuels in emerging technological and economic sectors worldwide [52]. It is estimated by the U.S. Renewable Fuels Standard that approximately 36 billion gallons of microalga-based biofuels will have been produced in the year 2022 [53].

Regarding sustainable aquatic and terrestrial animal feed, microalgae also present a very important role. These microorganisms can be a good alternative because, according to Dineshbabu et al. [54], their biomass is nutritionally richer than the traditional ones with respect to the protein, carotenoids, omega 3, and fatty acids content; besides, they contain antioxidative, antimicrobial, and disease-preventing molecules.

Currently, the population is increasing exponentially, and the projection is for it to increase to 9.8 billion by 2050 [55]. According to Hunter et al. [56], food production should increase by 25–60% to feed the entire population. On the other hand, aquaculture involves related activities such as rearing, breeding, and harvesting of freshwater and marine species of aquatic plants and fish, and around 70% of aquaculture yield worldwide is produced using external feed [55]; besides, the aquaculture emission of greenhouse has been increasing [57]. Then, in this scenario, microalgae also play a role in being economical and efficient, because using the biomass as feed or as a feed supplement can reduce the fish meal based on aquaculture. In the same way, microalgae can be mixed with animal feed and decrease the requirements for grain, which can be used to feed people.

References

1. Chew, K.W.; Yap, J.Y.; Show, P.L.; Suan, N.H.; Juan, J.C.; Ling, T.C.; Lee, D.-J.; Chang, J.-S. Microalgae biorefinery: High value products perspectives. Bioresour. Technol. 2017, 229, 53–62.
2. Hunt, R.W.; Zavalin, A.; Bhatnagar, A.; Chinnasamy, S.; Das, K.C. Electromagnetic biostimulation of living cultures for biotechnology, biofuel and bioenergy applications. Int. J. Mol. Sci. 2009, 10, 4515–4558.
3. Spanò, N.; Di Paola, D.; Albano, M.; Manganaro, A.; Sanfilippo, M.; D'Iglio, C.; Capillo, G.; Savoca, S. Growth performance and bioremediation potential of Gracilaria gracilis (Steentoft, L.M. Irvine & Farnham, 1995). Int. J. Environ. Stud. 2022, 79, 748–760.
4. Tu, R.; Jin, W.; Xi, T.; Yang, Q.; Han, S.-F.; Abomohra, A.E.-F. Effect of static magnetic field on the oxygen production of Scenedesmus obliquus cultivated in municipal wastewater. Water Res. 2015, 86, 132–138.

5. Han, S.; Jin, W.; Chen, Y.; Tu, R.; Abomohra, A.E.-F. Enhancement of lipid production of Chlorella pyrenoidosa cultivated in municipal wastewater by magnetic treatment. Appl. Biochem. Biotechnol. 2016, 180, 1043–1055.
6. Santos, L.O.; Deamici, K.M.; Menestrino, B.C.; Garda-Buffon, J.; Costa, J.A.V. Magnetic treatment of microalgae for enhanced product formation. World J. Microbiol. Biotechnol. 2017, 33, 169.
7. Zieliński, M.; Rusanowska, P.; Dębowski, M.; Hajduk, A. Influence of static magnetic field on sludge properties. Sci. Total Environ. 2018, 625, 738–742.
8. Bauer, L.M.; Costa, J.A.V.; da Rosa, A.P.C.; Santos, L.O. Growth stimulation and synthesis of lipids, pigments and antioxidants with magnetic fields in Chlorella kessleri cultivations. Bioresour. Technol. 2017, 244, 1425–1432.
9. Serrano, G.; Miranda-Ostojic, C.; Ferrada, P.; Wulff-Zotelle, C.; Maureira, A.; Fuentealba, E.; Gallardo, K.; Zapata, M.; Rivas, M. Response to Static Magnetic Field-Induced Stress in Scenedesmus obliquus and Nannochloropsis gaditana. Mar. Drugs 2021, 19, 527.
10. Costa, S.S.; Peres, B.P.; Machado, B.R.; Costa, J.A.V.; Santos, L.O. Increased lipid synthesis in the culture of Chlorella homosphaera with magnetic fields application. Bioresour. Technol. 2020, 315, 123880.
11. Deamici, K.M.; Santos, L.O.; Costa, J.A.V. Magnetic field action on outdoor and indoor cultures of Spirulina: Evaluation of growth, medium consumption and protein profile. Bioresour. Technol. 2018, 249, 168–174.
12. Small, D.P.; Hüner, N.P.; Wan, W. Effect of static magnetic fields on the growth, photosynthesis and ultrastructure of Chlorella kessleri microalgae. Bioelectromagnetics 2012, 33, 298–308.
13. Deamici, K.M.; Costa, J.A.V.; Santos, L.O. Magnetic fields as triggers of microalga growth: Evaluation of its effect on Spirulina sp. Bioresour. Technol. 2016, 220, 62–67.
14. Veiga, M.C.; Fontoura, M.M.; de Oliveira, M.G.; Costa, J.A.V.; Santos, L.O. Magnetic fields: Biomass potential of Spirulina sp. for food supplement. Bioprocess Biosyst. Eng. 2020, 43, 1231–1240.
15. Deamici, K.M.; Santos, L.O.; Costa, J.A.V. Magnetic field as promoter of growth in outdoor and indoor assays of Chlorella fusca. Bioprocess Biosyst. Eng. 2021, 44, 1453–1460.
16. Deamici, K.M.; de Morais, M.G.; Santos, L.O.; Muylaert, K.; Gardarin, C.; Costa, J.A.V.; Laroche, C. Static magnetic fields effects on polysaccharides production by different microalgae strains. Appl. Sci. 2021, 11, 5299.
17. Deamici, K.M.; Santos, L.O.; Costa, J.A.V. Use of static magnetic fields to increase CO2 biofixation by the microalga Chlorella fusca. Bioresour. Technol. 2019, 276, 103–109.

18. Chu, F.-J.; Wan, T.-J.; Pai, T.-Y.; Lin, H.-W.; Liu, S.-H.; Huang, C.-F. Use of magnetic fields and nitrate concentration to optimize the growth and lipid yield of Nannochloropsis oculata. J. Environ. Manag. 2020, 253, 109680.
19. Dębowski, M.; Zieliński, M.; Kisielewska, M.; Hajduk, A. Effect of constant magnetic field on anaerobic digestion of algal biomass. Environ. Technol. 2016, 37, 1656–1663.
20. Huo, S.; Chen, X.; Zhu, F.; Zhang, W.; Chen, D.; Jin, N.; Cobb, K.; Cheng, Y.; Wang, L.; Ruan, R. Magnetic field intervention on growth of the filamentous microalgae Tribonema sp. in starch wastewater for algal biomass production and nutrients removal: Influence of ambient temperature and operational strategy. Bioresour. Technol. 2020, 303, 122884.
21. Sirisha, K.; Suganya, B.; Sivasubramanian, V.; Bs, V.; Swaminathan, D.; Babu, A.; Meyyappan, N. Studies on the effect of pulsed magnetic field on the productivity of algae grown in dye industry effluent. J. Appl. Biotechnol. Bioeng. 2017, 3, 409–413.
22. Sambusiti, C.; Bellucci, M.; Zabaniotou, A.; Beneduce, L.; Monlau, F. Algae as promising feedstocks for fermentative biohydrogen production according to a biorefinery approach: A comprehensive review. Renew. Sustain. Energy Rev. 2015, 44, 20–36.
23. Goswami, R.K.; Mehariya, S.; Verma, P.; Lavecchia, R.; Zuorro, A. Microalgae-based biorefineries for sustainable resource recovery from wastewater. J. Water Process Eng. 2021, 40, 101747.
24. Jalilian, N.; Najafpour, G.D.; Khajouei, M. Macro and micro algae in pollution control and biofuel production—A review. ChemBioEng Rev. 2020, 7, 18–33.
25. Vieira, M.V.; Pastrana, L.M.; Fuciños, P. Microalgae encapsulation systems for food, pharmaceutical and cosmetics applications. Mar. Drugs 2020, 18, 644.
26. Santos, L.O.; Silva, P.G.P.; Costa, S.S.; Machado, T.B. Magnetic Field Application to Increase Yield of Microalgal Biomass in Biofuel Production. In Biotechnological Applications of Biomass; IntechOpen: London, UK, 2020.
27. Alam, M.A.; Xu, J.-L.; Wang, Z. Microalgae Biotechnology for Food, Health and High Value Products; Springer: Berlin/Heidelberg, Germany, 2020.
28. Esteves, A.F.; Soares, O.S.; Vilar, V.J.; Pires, J.C.; Gonçalves, A.L. The effect of light wavelength on CO2 capture, biomass production and nutrient uptake by green microalgae: A step forward on process integration and optimisation. Energies 2020, 13, 333.
29. Menegazzo, M.L.; Fonseca, G.G. Biomass recovery and lipid extraction processes for microalgae biofuels production: A review. Renew. Sustain. Energy Rev. 2019, 107, 87–107.
30. Debnath, C.; Bandyopadhyay, T.K.; Bhunia, B.; Mishra, U.; Narayanasamy, S.; Muthuraj, M. Microalgae: Sustainable resource of carbohydrates in third-generation biofuel production. Renew. Sustain. Energy Rev. 2021, 150, 111464.

31. de Carvalho Silvello, M.A.; Gonçalves, I.S.; Azambuja, S.P.H.; Costa, S.S.; Silva, P.G.P.; Santos, L.O.; Goldbeck, R. Microalgae-based carbohydrates: A green innovative source of bioenergy. Bioresour. Technol. 2022, 344, 126304.
32. Daneshvar, E.; Ok, Y.S.; Tavakoli, S.; Sarkar, B.; Shaheen, S.M.; Hong, H.; Luo, Y.; Rinklebe, J.; Song, H.; Bhatnagar, A. Insights into upstream processing of microalgae: A review. Bioresour. Technol. 2021, 329, 124870.
33. Berlot, M.; Rehar, T.; Fefer, D.; Berovic, M. The influence of treatment of Saccharomyces cerevisiae inoculum with a magnetic field on subsequent grape must fermentation. Chem. Biochem. Eng. Q. 2013, 27, 423–429.
34. Deutmeyer, A.; Raman, R.; Murphy, P.; Pandey, S. Effect of magnetic field on the fermentation kinetics of Saccharomyces cerevisiae. Adv. Biosci. Biotechnol. 2011, 2011, 6857.
35. Santos, L.O.; Alegre, R.M.; Garcia-Diego, C.; Cuellar, J. Effects of magnetic fields on biomass and glutathione production by the yeast Saccharomyces cerevisiae. Process Biochem. 2010, 45, 1362–1367.
36. da Silva, P.G.P.; Júnior, D.P.; Sala, L.; de Medeiros Burkert, J.F.; Santos, L.O. Magnetic field as a trigger of carotenoid production by Phaffia rhodozyma. Process Biochem. 2020, 98, 131–138.
37. Tan, L.; Shao, Y.; Mu, G.; Ning, S.; Shi, S. Enhanced azo dye biodegradation performance and halotolerance of Candida tropicalis SYF-1 by static magnetic field (SMF). Bioresour. Technol. 2020, 295, 122283.
38. Zhang, J.; Zhou, K.; Wang, L.; Gao, M. Extremely low-frequency magnetic fields affect pigment production of Monascus purpureus in liquid-state fermentation. Eur. Food Res. Technol. 2014, 238, 157–162.
39. Gao, M.; Zhang, J.; Feng, H. Extremely low frequency magnetic field effects on metabolite of Aspergillus niger. Bioelectromagnetics 2011, 32, 73–78.
40. Canli, O.; Kurbanoglu, E.B. Application of low magnetic field on inulinase production by Geotrichum candidum under solid state fermentation using leek as substrate. Toxicol. Ind. Health 2012, 28, 894–900.
41. Menestrino, B.d.C.; Pintos, T.H.C.; Sala, L.; Costa, J.A.V.; Santos, L.O. Application of static magnetic fields on the mixotrophic culture of Chlorella minutissima for carbohydrate production. Appl. Biochem. Biotechnol. 2020, 192, 822–830.
42. Pérez, A.T.E.; Camargo, M.; Rincón, P.C.N.; Marchant, M.A. Key challenges and requirements for sustainable and industrialized biorefinery supply chain design and management: A bibliographic analysis. Renew. Sustain. Energy Rev. 2017, 69, 350–359.

43. Pessôa, L.C.; Deamici, K.M.; Pontes, L.A.M.; Druzian, J.I.; de Jesus Assis, D. Technological prospection of microalgae-based biorefinery approach for effluent treatment. Algal Res. 2021, 60, 102504.
44. Wang, Y.; Ho, S.-H.; Cheng, C.-L.; Guo, W.-Q.; Nagarajan, D.; Ren, N.-Q.; Lee, D.-J.; Chang, J.-S. Perspectives on the feasibility of using microalgae for industrial wastewater treatment. Bioresour. Technol. 2016, 222, 485–497.
45. Ferreira, G.F.; Rios Pinto, L.F.; Carvalho, P.O.; Coelho, M.B.; Eberlin, M.N.; Maciel Filho, R.; Fregolente, L.V. Biomass and lipid characterization of microalgae genera Botryococcus, Chlorella, and Desmodesmus aiming high-value fatty acid production. Biomass Convers. Biorefinery 2021, 11, 1675–1689.
46. Suganya, T.; Varman, M.; Masjuki, H.; Renganathan, S. Macroalgae and microalgae as a potential source for commercial applications along with biofuels production: A biorefinery approach. Renew. Sustain. Energy Rev. 2016, 55, 909–941.
47. Costa, J.A.V.; Freitas, B.C.B.; Cruz, C.G.; Silveira, J.; Morais, M.G. Potential of microalgae as biopesticides to contribute to sustainable agriculture and environmental development. J. Environ. Sci. Health Part B 2019, 54, 366–375.
48. Bhattacharjee, R.; Dey, U. Biofertilizer, a way towards organic agriculture: A review. Afr. J. Microbiol. Res. 2014, 8, 2332–2343.
49. Thirumurthy, P.; Mol, I. Microalgae as bio-pesticides for the development of sustainable agriculture. Wide Spectr. 2020, 6, 5–22.
50. Costa, J.A.V.; Cassuriaga, A.P.A.; Moraes, L.; de Morais, M.G. Biosynthesis and potential applications of terpenes produced from microalgae. Bioresour. Technol. Rep. 2022, 101166.
51. Stirk, W.; Bálint, P.; Tarkowská, D.; Novák, O.; Maróti, G.; Ljung, K.; Turečková, V.; Strnad, M.; Ördög, V.; Van Staden, J. Effect of light on growth and endogenous hormones in Chlorella minutissima (Trebouxiophyceae). Plant Physiol. Biochem. 2014, 79, 66–76.
52. GMI (Global Market Insights). Algae Oil Market Size, Regional Outlook, Application Growth Potential, COVID-19 Impact Analysis, Competitive Market Growth & Forecast, 2022–2028; Global Market Insights Inc.: Selbyville, DE, USA, 2022.
53. Qari, H.; Rehan, M.; Nizami, A.-S. Key issues in microalgae biofuels: A short review. Energy Procedia 2017, 142, 898–903.
54. Dineshbabu, G.; Goswami, G.; Kumar, R.; Sinha, A.; Das, D. Microalgae—Nutritious, sustainable aqua-and animal feed source. J. Funct. Foods 2019, 62, 103545.
55. The State of World Fisheries and Aquaculture 2018—Meeting the Sustainable Development Goals; The State of The World series of the Food and Agriculture Organization of the United

Nations. Aquaculture; FAO: Rome, Italy, 2018; Volume 35.

56. Hunter, M.C.; Smith, R.G.; Schipanski, M.E.; Atwood, L.W.; Mortensen, D.A. Agriculture in 2050: Recalibrating targets for sustainable intensification. Bioscience 2017, 67, 386–391.

57. Hasan, M.; Soto, D. Improving Feed Conversion Ratio and Its Impact on Reducing Greenhouse Gas Emissions in Aquaculture; FAO: Rome, Italy, 2017.