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Microalgae-based carbon sequestration to mitigate climate change and application of nanomaterials in algal biorefinery

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ABSTRACT

Carbon sequestration is an emergent technique to combat the augmented concentration of carbon dioxide in the environment. Unlike the carbon emission reduction strategies, carbon sequestration exhibits prominent potential to alleviate the carbon dioxide levels or conceal carbon dioxide emission if the carbon dioxide is to be arrested from voluminous stationary sources and effective use of the captured carbon dioxide to generate chemical and energy. Lately, microalgae systems are employed in biological sequestration or mitigation of carbons. These systems depict a hopeful and workable substitution to presently employed carbon mitigation approaches. Generally, microalgae are composed of highly multifarious and fast-growing microorganism groups that are very much proficient in photoautotrophic, heterotrophic, and mixotrophic environments. Cultivation of these microalgae can be performed on non-fertile land with a unit carbon dioxide fixation capacity 10–50 times higher than terrestrial plants. Additionally, this microalgae biomass can also generate food, feed, fine chemicals, and biofuels which further shows the widespread advantages of microalgae-based carbon dioxide fixation. In this current review article, few important insights on how microalgae embody various forms of carbons and provide a precise summary of the present development in the proficient use of microalgae for carbon dioxide fixation, algal biorefinery concept, and extraction of various value-added products are discussed.

Keywords:*Microalgae; carbon sequestration; climate change; nanomaterials; algal biorefinery*

1. INTRODUCTION

The augmentation of carbon dioxide in the atmosphere aggravated the risks regarding climate change by provoking the temperature of the atmosphere (Cassia et al., 2018). Almost, an increase of 2 °C is observed in global temperature as well as the carbon dioxide level also doubled. The mitigation strategy of carbon dioxide employing algae is one of the promising techniques to alleviate greenhouse gas emissions and could be easily replaceable with the existing technologies (Zhou et al., 2017). Due to different anthropogenic activities, the rising levels of greenhouse gases such as carbon dioxide, methane, nitrous oxides, or fluorinated gasses have been observed in the atmosphere. If the ecosystem cycle (capture, accumulation, and release) of carbon is observed closely, it can be inferred that carbon has an equilibrium leading to a balanced distribution among different levels of the atmosphere (such as hydrosphere, lithosphere, atmosphere, and biosphere) (Dilmore et al., 2018). However, this equilibrium got quite destabilized due to the interference of humans mostly with the beginning of the industrial era. The rapid exploitation of natural sources led to the exponential deterioration of the environment. The existing carbon dioxide sequestering technologies can be categorized mainly into two potential groups which are physical and biological. Generally, if forestation is taken into account then it is observed that the elementary approach is captured by various plants with the help of photosynthesis (Mikulčić et al., 2019; Razzak et al., 2013). Though, other microorganisms like algae or microalgae play a vital role in this critical duty.

Microalgae generate a major amount of the atmospheric oxygen and ingest carbon dioxide, which accounts for a significant quantity (~50%) of the photosynthesis on the earth (Cuellar-Bermudez et al., 2015). Employing anthropogenic carbon dioxide, the algal biomass generates a carbon-neutral, sustainable fuel source that is compatible with the environment (Rahman et al., 2017). Mostly the microalgae's photosynthetic efficiency lies around ~11–20 % which is more than the terrestrial plants (~1–2 %). In the case of a few algal species, their biomass in periods got doubled as short as three and a half hours during their exponential growth (Razzak et al., 2013). Besides, the benefits of being tolerant of carbon dioxide's (flue gas) a higher degree of concentration, requirements of low light intensity, environmentally sustainability, and co-producing valuable products make these microalgae a great choice of organisms (Singh and Ahluwalia, 2013; Jaiswal et al., 2020a). As per the studies presented by Intergovernmental Panel on Climate Change (IPCC), deforestation has alleviated carbon dioxide sequestration by a huge quantity (around ~20% of the greenhouse gas presented in the atmosphere). Carbon dioxide sequestration by the help of plants and microalgae has a significant biological value(Yamasaki, 2003). From observed reports on global conditions, it was found that the total emission of carbon dioxide has already risen to 48 Gigatons (Gt) in 2010 (taken account of all sources of emissions). Lately, the studies suggested that if we have to limit global warming to 2 °C the median level of emissions has to be mitigated to 44 GT. According to the UNFCCC Kyoto Protocol, Some useful actions should be taken to reduce the earth's temperature such as geoengineering, application of large-scale environmental engineering to resist the negative changes in atmospheric chemistry, specifically to reduce greenhouse gas, carbon dioxide concentrations (Burniaux et al., 2008; Toichi, 2012).

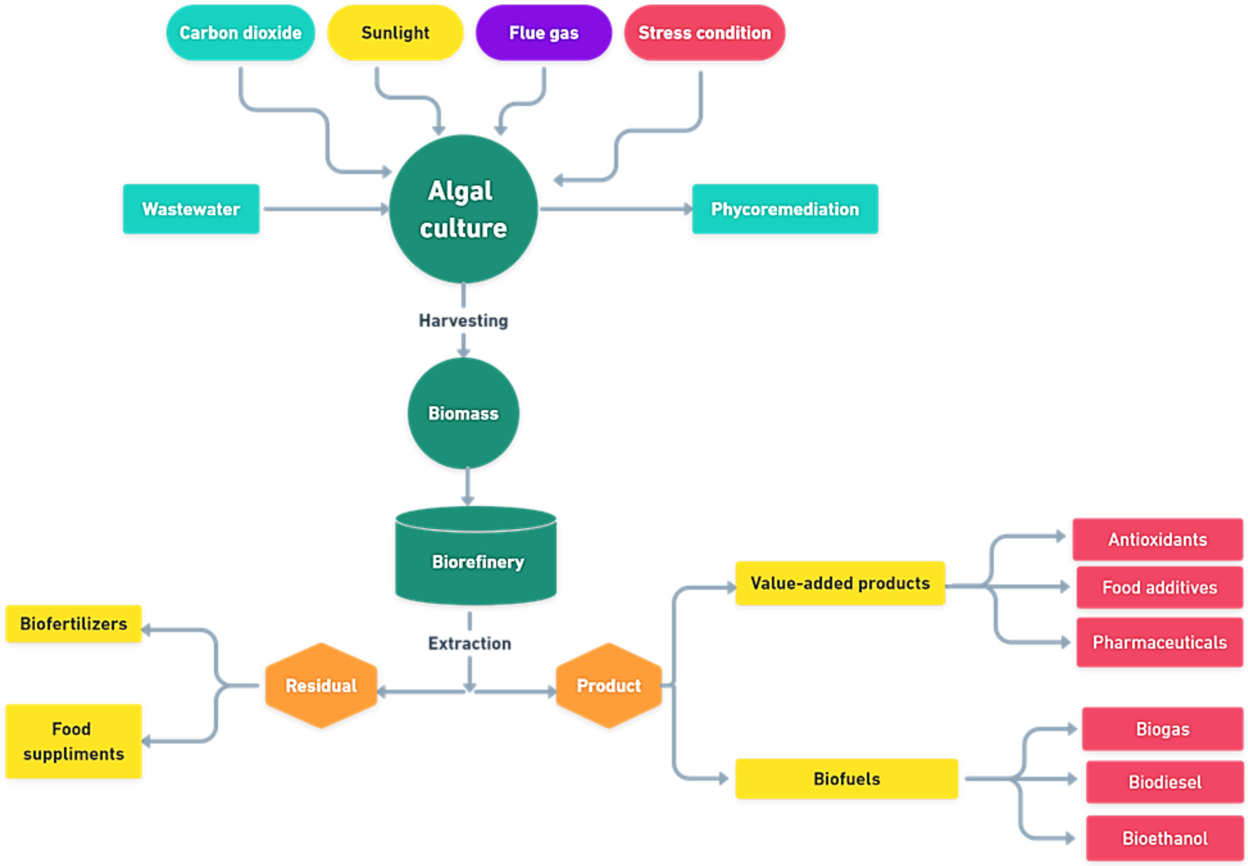

Figure 1. Schematic representation of algal cultivation and biorefinery.

2. MICROALGAE AS A POTENTIAL CARBON-CAPTURING AGENT

The increased concentration of greenhouse gases is the primary cause of climatic changes such as increased temperature, the changed pattern of rainfall, rising sea levels, floods, droughts, and the occurrence of various extreme climatic phenomena as an outcome of global warming (Van Aalst, 2006). The higher concentration of CO_2 has a great contributor to global warming. The primary cause is the overuse of fossil fuels and increased carbon dioxide emission. A budget-friendly and eco-friendly sustainable approach to overcoming the burning issue of increased carbon dioxide emissions would be the bio-sequestration of CO_2using microalgae cell factories (Kassim and Meng, 2017; Yadav and Sen, 2017). By using microalgae for carbon sequestration is a highly emerging and promising way to convert CO_2 into biomass *via* photosynthesis. Microalgae have a better ability to fix CO_2 compared to C4 plants (Cheah et al., 2016). Simultaneously, microalgal biomass is used for the production of renewable biofuels, food, animal, and aquaculture feed products, and other value-added products such as cosmetics, nutraceuticals, pharmaceuticals, bio-fertilizers, bioactive substances. Microalgae cultivation is much easier than conventional forestry, agricultural, and aquatic plants as they can survive well in any extreme environment like high temperature, saline-alkaline soil, land, and water. Even they can grow on the contaminated wastewater (Gouveia, 2015; Sankaran et al., 2018). As they can be fed with toxic waste gasses such as CO_2, NO_x, and SO_x from flue gas, inorganic and organic carbon, N, P, and other pollutants from agricultural, industrial, and sewage wastewater sources. So the propagation of microalgae can be used to transform those elements into bioenergy (Arora et al., 2020; Fatima et al., 2020a, 2020b; Jaiswal et al., 2014a, 2016, 2020b). Microalgae can be cultivated in open arable land or closed photobioreactor. The simple cellular structure with high lipid content and high photosynthetic efficiency makes them a potential choice for both biological carbon sequestrations and biomass production (Brennan and Owende, 2010; Jaiswal et al., 2020a).

3. ADVANTAGES OF MICROALGAE-BASED CARBON SEQUESTRATION

The cultivation of photosynthetic microalgae is one of the unique alternatives for carbon mitigation from the environment and it can meet all the requirements for easy carbon sequestration (Farrelly et al., 2013). Microalgae carbon mitigation is more advantageous than that of other terrestrial plant systems because of their simple harvesting systems and fast production, low light intensity requirements, extreme tolerance to environmental stresses, high CO_2 tolerance, increased photosynthetic ability, and increased biomass production rate (Mata et al., 2010). Many algal species can grow exponentially and quickly double their biomass. They are efficient to convert solar energy to biomass. Two fast-growing microalgae such as *Chlorella*sp. and *Synechococcu*s sp. show a high biomass production rate. Various recent studies have shown that the microalgae can attain a 10-20% higher rate of photosynthetic efficiency than the terrestrial trees (Al-Haj et al., 2014). Microalgae can tolerate a high level of CO_2 concentration for their optimum growth and can efficiently fix CO_2 than the higher plants. The source of carbon can be atmospheric CO_2, industrial exhaust gases, and soluble carbonates (e.g. sodium bicarbonate and sodium carbonate). Microalgae can fix high concentrations of CO_2 present in the flue gases exhausted from the industries as they are highly tolerant to the high CO_2 concentration (Wang et al., 2008). Using various thermophiles microalgae is the economical and prospective approach to mitigate CO_2 from the environment by lowering the cooling cost. Microalgae can thrive in wastewater (industrial wastewater, agricultural waste, and municipal wastewater) and utilize various trace elements and heavy metals present in that water for their growth. So, this advantage of microalgae can be used in bioremediation especially wastewater treatment and heavy metal removal from water bodies (Show et al., 2017; Harun et al., 2010; Jaiswal et al., 2020c).

4. ALGAL BIOREFINERY AND VALUE-ADDED PRODUCTS

Using the advantages of the high and fast growth rate of microalgae, and high production of biomass within a short period are being utilized by the microalgal biotechnology companies significantly (Huang et al., 2010). Those companies are flourishing day by day. High levels of carbohydrate, protein, lipid, and other nutrients containing algal biomass can be utilized by converting those into various commercially value-added products and fuels (Khanra et al., 2018). Entirely this concept can be referred to as microalgal biorefinery which can be used as an alternative source of energy to meet the energy crisis and restore a clean safe environment (Kumar et al., 2020) (Figure 1). AS the oil reservoirs are getting depleted, there is a strong need to find an eco-friendly way to produce fuel to meet the energy requirements. Microalgae biomass is a very good feedstock for biofuel, biodiesel, biogas, biohydrogen, bioethanol, and biobutanol production. Various microalgae such as *Chlorella*, *Dunaliella*, *Isochrysis*, *Nannochloris*, *Nannochloropsis*, *Neochloris*, *Phaeodactylum*, *Porphyridium*, and *Schizochytrium* contain a high concentration of triacylglycerol and their transesterification produce biodiesel (Lafarga, 2020; Jaiswal et al., 2014b). Glycerol is produced as a by-product which also has high commercial value. Leftover, algal biomass can be used as an animal deed or as compost. Anaerobic digestion of microalgae biomass can produce environmentally sustainable biogas (Saratale et al., 2018; Jha et al., 2016). Fermenting the carbohydrate content present in the biomass can produce bioethanol and biobutanol. Other than the algal biomass, various algal metabolites especially pigments such as chlorophyll a and b, lutein, astaxanthin, β-carotene, phycobilins, C-phycocyanin have found wide application in dyes, cosmetics, food and feed additives, nutraceuticals and pharmaceuticals, as natural dyes, bioactive components, anti-oxidants, nutritive and neuroprotective agents (Chandra et al., 2019). Microalgae, such as *Nannochloropsis*, *Tetraselmis*, and *Isochrysis* are utilized for health supplements and medicine. Extracellular polymeric substances (EPSs) and polyhydroxyalkanoates (PHAs) are exploited in bio-plastic production and industrial applications (Koutra et al., 2018).

5. APPLICATION OF NANOMATERIALS IN AN ALGAE BIOREFINERY

Microalgae biomass can be transformed into cosmetics, chemicals, food, feed, medicines, fertilizers, biofuels, and value-added compounds in the microalgae biorefinery where additional usage of nanomaterials became a very attractive choice in recent trends (Bilad et al., 2014; Slade et al., 2013; Christenson et al., 2011; Wang et al., 2015). With the help of nanotechnology,unique behaviors and characteristics are being observed in various factors of microalgae. Mostly, the usage of nanomaterial assists in microalgae cultivation biochemical compounds accumulation, extraction, and conversion methods as a catalyst or catalyst support (Bilad et al., 2014; Slade et al., 2013; Christenson et al., 2011). Still, many of the nanomaterial applications in the case of microalgae biorefinery are under observation and aiming for further improvement.

Metallic nanoparticles and hybrid nanoparticles are being frequently used in the cultivation of microalgae (Table 1). In various reports, researchers have tried to investigate the effect of nanomaterials in microalgae cultivation by varying the type of nanomaterials, varying the concentrations, and even the size of nanomaterials (He et al., 2017). The synthesis of different types of nanomaterials (graphene oxide, Fe_3O_4, ZnO, TiO_2, etc.) has been investigated with its properties for numerous applications (Jaiswal et al., 2018a, 2018b, 2020d; Dutta et al., 2019, 2020; Ahmad et al., 2020a, 2020b,2020c; Sudhakar et al., 2017, 2018). These nanoparticles can serve the potential in the application of algal biorefinery. The resultant impact of the employed nanomaterials reflected on the growth rate, biomass production and accumulation of intracellular compounds of the microalgae. In some studies, it is been observed that metallic nanoparticles which are found in some wastewater may complement the scarcity of the minerals and nutrients which microalgae need to grow (Radzun et al., 2015). So from several kinds of research, we can conclude that these nanomaterials help to improve microbial activities, and thus, it makes a positive impact on lipid accumulation as well as in microalgae cultivation (Windt et al., 2005). In the given table we have shown some of the nanomaterials which have been utilized by different researchers in various species.Alongside the contribution towards microalgae cultivation, nanomaterials make significant impacts on the harvesting efficiency of microalgae (Table 2). Mostly in the case of harvesting, magnetic nanoparticles are being used because of their recyclability, speed, automation, cost-effectiveness, scalability, and harvesting performance (Jaiswal et al., 2020e). Moreover, these particles have the advantages of easy separation from microalgae (Borlido et al., 2013; Zhu et al., 2017). To observe magnetic separation studies, Fraga-Garcia et al. employed iron oxide nanoparticles in a magnetic-based microalgae harvesting system and the recorded harvesting efficiencies were more than 95%. Japar et al., (2017) also investigated with iron oxide nanoparticles on *Chlorella* sp. UKM2 and *Coelastrella* sp. UKM4 cultures and found that the harvesting efficiency was around 94% (Japar et al., (2017). Among the magnetic particles, ferric oxide (Fe_3O_4) is the most frequently employed magnetic nanoparticles because of its advantageous surface-area, magnetism, and biocompatibility characteristics (Xu et al., 2011; Hu et al., 2013).

Table 1. Microalgae growth assisted with the doses of nanomaterials.

Microalgae		**Nanomaterials**		**Performances**		**References**
Species	**Density (cells/mL)**	**Types of NPs**	**Dosage (mg/L)**	**Efficiency (%)**	**Time (days)**	
Scenedesmusobliquus	5×10^6	magnesium oxide	~40.0	18.5	6	He et al., 2017
Scenedesmusobliquus	1×10^7	carbon nanotubes	~5.0	8.9	8	He et al., 2017
Scenedesmusobliquus	1×10^7	ferric oxide (Fe_2O_3)	≤ 20.0	10	7	He et al., 2017
Scenedesmusobliquus	1×10^7	ferricoxide (Fe_2O_3)	~5.0	39.6	7	He et al., 2017
Desmodesmussubspicatus	1×10^5	nanoscale zero-valence iron	~5.1	58.33	9	Padrova et al., 2015
Dunaliella salina	1×10^5	nanoscale zero-valence iron	~5.1	33.33	9	Padrova et al., 2015
Parachlorellakessleri	1×10^5	nanoscale zero-valence iron	~5.1	17	9	Padrova et al., 2015
Raphidocelissubcapitata	1×10^5	nanoscale zero-valence iron	~5.1	45.24	9	Padrova et al., 2015
Nannochloropsis limnetica	1×10^5	nanoscale zero-valence iron	~5.1	37.14	9	Padrova et al., 2015
Trachydiscusminutus	1×10^5	nanoscale zero-valence iron	~5.1	33.21	9	Padrova et al., 2015

Table 2. Microalgae harvesting using engineered nanoparticles.

Microalgae		**Nanomaterials**		**Performances**		**References**
Species	**Density (g/L)**	**Types of NPs**	**Dosage (g/L)**	**Efficiency (%)**	**Time (days)**	
Microcystisaeruginosa	0.869	naked magnetic nanoparticles	0.50	99.6	5	Lin et al., 2015
Microcystisaeruginosa	0.869	reactivated/MNPs mixture	0.17	>93.8	5	Lin et al., 2015
Microcystisaeruginosa	0.500	PEI-Fe_3O_4	0.10	>70.0	5	Yang et al., 2018
Microcystisaeruginosa	0.600	PEI-Fe_3O_4	0.10	>80.0	5	Yang et al., 2018
Scenedesmusdimorphus	0.800	PEI-Fe_3O_4	0.07	>80.0	3	Ge et al., 2015a
Scenedesmusdimorphus	0.800	PEI-Fe_3O_4	0.15	>80.0	3	Ge et al., 2015a

Scenedesmusdimorphus	1.000	PEI-Fe_3O_4	0.60	82.7	2–3	Ge et al., 2015b
Scenedesmusdimorphus	0.800	stearic acid-Fe_3O_4-ZnO	-	-	5	Ge et al., 2015c
Scenedesmusovalternus	0.600	bare Fe_3O_4	0.50	>95.0	5	Fraga-Garcia et al., 2018
Scenedesmusobliquus	1.700	MgAC-Fe_3O_4	4.72	>80.0	10	Kim et al., 2018

6. CONCLUSIONS

Cultivation of microalgae can be done in several environments maintaining optimum growth rate and carbon fixation sufficiency. Moreover, these can act as renewable biomass raw materials to generate various value-added products such as biodiesel, bioethanol, pigments, health supplements, and medicines. Multiples literature has depicted that different strains of microalgae are useful in assimilating inorganic and organic carbons from plenty of important sources. Most of the microalgae cultivation operations are suitable for applications engineered to mitigate carbon. Nevertheless, the embodiment of microalgae-based carbon sequestration technologies for large-scale application has yet to be measured in terms of efficacy and cost-effectiveness. Some advancements and novel notions in the following areas are required before microalgae-based approaches utilization for commercial-scale application: optimized approaches to address carbon sources with various forms of chemical and distribution characteristics, screening and genetic engineering of noble performance strains, improving usages of industrial waste gases, a profound understanding of the mechanisms of microalgae-based carbon fixation, ameliorative carbon dioxide transfer, and oxygen desorption, cultivation process optimization and scaling up, cost-effective photobioreactor, highly efficacious microalgae harvesting and conversion approaches, and development of value-added products. Moreover, the techno-economic analysis must be employed using production facilities to optimize economic feasibility with a reasonable scale. Development of life cycle assessment models and assesses the environmental influences of microalgae-based carbon sequestration using these models are also necessary. In upcoming times, the advancement of microalgae-based carbon mitigation will be hopefully achieved and the application range will be much broader which will be providing environmental and economic convenience of the usage of microalgae.

7. REFERENCES

1. Ahmad W., Jaiswal K.K., Soni S., (2020a). Green synthesis of titanium dioxide (TiO_2) nanoparticles by using *Menthaarvensis* leaves extract and its antimicrobial properties. *Inorganic and Nano-Metal Chemistry*, 50 (10): 1032–1038. https://doi.org/10.1080/24701556.2020.1732419
2. Ahmad W., Jaiswal K.K., Amjad M., (2020b). *Euphorbia herita* leaf extract as a reducing agent in a facile green synthesis of Iron oxide nanoparticles and antimicrobial activity evaluation. *Inorganic and Nano-Metal Chemistry*. 1–8. https://doi.org/10.1080/24701556.2020.1815062
3. Ahmad W., Singh A., Jaiswal K.K., Gupta P., (2020c). Green Synthesis of Photocatalytic TiO_2 Nanoparticles for Potential Application in Photochemical Degradation of Ornidazole. *Journal of Inorganic and Organometallic Polymers and Materials*. https://doi.org/10.1007/s10904-020-01703-6
4. Al-Haj L.A., (2014). Development of genetic engineering tools for the cyanobacterium*Synechocystis* PCC 6803 for advanced biofuel production (Doctoral dissertation, UCL (University College London).
5. Arora N., Jaiswal K.K., Kumar V., Vlaskin M.S., Nanda M., Pruthi V., Chauhan P.K., (2020). Small-scale phyco-mitigation of raw urban wastewater integrated with biodiesel production and its utilization for aquaculture. *Bioresource Technology*, 297: 122489. https://doi.org/10.1016/j.biortech.2019.122489
6. Bilad R.M., Discart V., Vandamme D., Foubert I., Muylaert K., Vankelecom J.F.I., (2014). Coupled cultivation and pre-harvesting of microalgae in a membrane photobioreactor (MPBR). *Bioresour. Technol.*, 155: 410–417. https://doi.org/10.1016/J.BIORTECH.2013.05.026.
7. Borlido L., Azevedo A.M., Roque A.C.A., Aires-Barros M.R., (2013). Magnetic separations in biotechnology. *Biotechnol. Adv.*, 31: 1374–1385. https://doi.org/10.1016/J.BIOTECHADV.2013.05.009.
8. Brennan L., Owende P., (2010). Biofuels from microalgae—a review of technologies for production, processing, and extractions of biofuels and co-products. *Renewable and Sustainable Energy Reviews*, 14(2): 557-577.
9. Burniaux J.M., Chateau J., Duval R., Jamet S., (2008). The economics of climate change mitigation: Policies and options for the future.
10. Cassia R., Nocioni M., Correa-Aragunde N., Lamattina L., (2018). Climate Change and the Impact of Greenhouse Gasses: CO_2 and NO, Friends and Foes of Plant Oxidative Stress. *Frontiers in Plant Science*, 9: 273. https://doi.org/10.3389/fpls.2018.00273
11. Chandra R., Iqbal H.M., Vishal G., Lee H.S., Nagra S., (2019). Algal biorefinery: A sustainable approach to valorize algal-based biomass towards multiple product recovery. *BioresourceTechnology*, 278: 346-359.
12. CheahW.Y., Ling T.C., Juan J.C., Lee D.J., Chang J.S., Show P.L., (2016). Biorefineries of carbon dioxide: From carbon capture and storage (CCS) to bioenergies production. *Bioresource Technology*, 215: 346-356.
13. Christenson L., Sims R., (2011). Production and harvesting of microalgae for wastewater treatment, biofuels, and

bioproducts. *Biotechnol. Adv.*, 29: 686–702. https://doi.org/10.1016/J.BIOTECHADV.2011.05.015.

14. Cuellar-Bermudez S.P., Garcia-Perez J.S., Rittmann B.E., Parra-Saldivar R., (2015). Photosynthetic bioenergy utilizing CO_2: an approach on flue gases utilization for third generation biofuels. *Journal of Cleaner Production*, 98: 53-65.
15. Dilmore R., Zhang L., (2018).Greenhouse gases and their role in Climate Change. In Greenhouse Gases and Clay Minerals. Springer, Cham, (pp. 15-32).
16. Dutta S., Banerjee I., Jaiswal K.K. (2020). Graphene and graphene-based nanomaterials for biological and environmental applications for sustainability. *Octa Journal of Biosciences*, 8 (2): 106-112.
17. Dutta S., Jaiswal K.K., Verma R., Basavarajud D.M., RamaswamyA.P., (2019). Green synthesis of zinc oxide catalyst under microwave irradiation using banana (*Musa spp.*) corm (rhizome) extract for biodiesel synthesis from fish waste lipid.*Biocatalysis and Agricultural Biotechnology*, 22: 101390. https://doi.org/10.1016/j.bcab.2019.101390
18. Farrelly D.J., Everard C.D., Fagan C.C., McDonnell K.P. (2013). Carbon sequestration and the role of biological carbon mitigation: a review. *Renewable and Sustainable Energy Reviews*, 21: 712-727.
19. Fatima N., Kumar V., Rawat B.S., Jaiswal K.K., (2020a). Enhancing algal biomass production and nutrients removal from municipal wastewater via a novel mini photocavity bioreactor. *Biointerface Research in Applied Chemistry*, 10 (1): 4714–4720.
20. Fatima N., Kumar V., Vlaskin M.S., Jaiswal K.K., Jyoti, Gururani P., Kumar S., (2020b). Toxicity of Cadmium (Cd) on microalgae growth (IC50 value) and its exertions in biofuel production. *Biointerface Research in Applied Chemistry*, 10 (4): 5828–5833.
21. Fraga-Garcia P., Kubbutat P., Brammen M., Schwaminger S., Berensmeier S., (2018). Bare iron oxide nanoparticles for magnetic harvesting of microalgae: from interaction behavior to process realization. *Nanomaterials*, 8: 292. https://doi.org/10.3390/nano8050292.
22. Ge S., Agbakpe M., Wu Z., Kuang L., Zhang W., Wang X., (2015b). Influences of surface coating, UV irradiation and magnetic field on the algae removal using magnetite nanoparticles. *Environ. Sci. Technol.*, 49: 1190–1196. https://doi.org/10.1021/es5049573.
23. Ge S., Agbakpe M., Zhang W., Kuang L., (2015a). Heteroaggregation between PEI-coated magnetic nanoparticles and algae: effect of particle size on algal harvesting efficiency. *ACS Appl. Mater. Interfaces*., 7: 6102–6108. https://doi.org/10.1021/acsami.5b00572.
24. Ge S., Agbakpe M., Zhang W., Kuang L., Wu Z., Wang X., (2015c). Recovering magnetic Fe_3O_4–ZnO nanocomposites from algal biomass based on hydrophobicity shift under UV irradiation. *ACS Appl. Mater. Interfaces*., 7: 11677–11682. https://doi.org/10.1021/acsami.5b03472.
25. Gouveia L., (2015). From tiny microalgae to huge biorefineries. New microbial technologies for advances biofuels: toward more sustainable production methods. Apple Academic Press, Ontario, 55-76.
26. Harun R., Singh, M., Forde, G.M., Danquah, M.K., (2010). Bioprocess engineering of microalgae to produce a variety of consumer products. *Renewable and Sustainable Energy Reviews*, 14(3): 1037-1047.
27. He M., Yan Y., Pei F., Wu M., Gebreluel T., Zou S., Wang C., (2017). Improvement on lipid production by *Scenedesmusobliquus* triggered by low dose exposure to nanoparticles. *Sci. Rep.*, 7: 15526. https://doi.org/10.1038/s41598-017-15667-0.
28. Hu Y.R., Wang F., Wang S.K., Liu C.Z., Guo C., (2013). Efficient harvesting of marine microalgae *Nannochloropsis maritima* using magnetic nanoparticles. *Bioresour.Technol.*, 138: 387–390. https://doi.org/10.1016/J.BIORTECH.2013.04.016.
29. Huang G., Chen, F., Wei, D., Zhang, X., Chen, G. (2010).Biodiesel production by microalgal biotechnology. *Applied Energy*, 87(1): 38-46.
30. Jaiswal K.K., Pandey H., (2014a). Next generation renewable and sustainable micro-fuels from Chlorella pyrenoidosa. *International Journal of Recent Scientific Research*, 5 (4): 767-769.
31. Jaiswal K.K., Jha B., Prasath R.A., (2014b). Biodiesel production from discarded fish waste for sustainable clean energy development. *Journal of Chemical and Pharmaceutical Sciences*, Special issue 4: 113-114.
32. Jaiswal K.K., Prasath R.A. (2016). Integrated growth potential of Chlorella pyrenoidosa using hostel mess wastewater and its biochemical analysis. *International Journal of Environmental Sciences*, 6 (5): 592-599.
33. Jaiswal K.K., Manikandan D., Murugan R., Ramaswamy A.P., (2018a). Microwave-assisted rapid synthesis of Fe3O4/poly(styrene-divinylbenzene-acrylic acid) polymeric magnetic composites and investigation of their structural and magnetic properties. *European Polymer Journal*., 98 (C): 177–190. https://doi.org/10.1016/j.eurpolymj.2017.11.005
34. Jaiswal K.K., Sudhakar S., Ramaswamy A.P., (2018b). ‘Graphene’ - World’s Thinnest Material for Revolutionizing Applications. *Everyman’s Science*, 53 (4): 219-223.
35. Jaiswal K.K., Banerjee I., Singh D., Sajwan P., Chhetri V., (2020a). Ecological stress stimulus to improve microalgae biofuel generation: a review. *Octa Journal of Biosciences*, 8 (1): 48–54.

36. Jaiswal K.K., Kumar V., Vlaskin M.S., Sharma N., Rautela I., Nanda M., Arora N., Singh A., Chauhan P.K., (2020b). Microalgae fuel cell for wastewater treatment: Recent advances and challenges. *Journal of Water Process Engineering,* 38: 101549. https://doi.org/10.1016/j.jwpe.2020.101549
37. Jaiswal K.K., Vlaskin M.S., Kumar V., (2020c). Impact of glyphosate herbicide stress on metabolic growth and lipid inducement in *Chlorella sorokiniana* UUIND6 for biodiesel production. *Algal Research,* 51: 102071. https://doi.org/10.1016/j.algal.2020.102071
38. Jaiswal K.K., Dutta S., Pohrmen C.B., Verma R., Kumar A., Ramaswamy A.P., (2020d). Bio-waste Chicken Eggshell-derived Calcium Oxide for Photocatalytic Application in Methylene Blue Dye Degradation under Natural Sunlight Irradiation. *Inorganic and Nano-Metal Chemistry,* 1–10. https://doi.org/10.1080/24701556.2020.1813769
39. Jaiswal K.K., Pathak V.V., Ramaswamy A.P., (2020e). Magnetic harvesting of microalgae biomass for cost-effective algal biofuel production. In: *Algal Biofuel: Sustainable Solution*. Kothari Richa, Vinayak V Pathak, and VV Tyagi (editors). New Delhi, India: The Energy and Resources Institute. pp. 139–148.
40. Jha B., Jaiswal K.K., Ramaswamy A.P., (2016). Impact of poly-aluminium chloride on foam suppression in a chicken waste-based biogas plant: A case study at KEPCO Kerala. *International Journal of Environmental Sciences,* 6 (6): 934-940.
41. Kassim M.A., Meng, T.K., (2017). Carbon dioxide (CO_2) biofixation by microalgae and its potential for biorefinery and biofuel production. *Science of the Total Environment,* 584: 1121-1129.
42. Khanra S., Mondal, M., Halder, G., Tiwari, O.N., Gayen, K., Bhowmick T.K., (2018). Downstream processing of microalgae for pigments, protein and carbohydrate in industrial application: A review. Food and bioproducts processing, 110: 60-84.
43. Kim B., Bui V., Farooq W., Jeon S., Oh Y.K., Lee Y.C., (2018). Magnesium aminoclay-Fe_3O_4 (MgAC-Fe_3O_4) hybrid composites for harvesting of mixed microalgae. *Energies*, 11: 1359. https://doi.org/10.3390/en11061359.
44. Koutra E., Economou C.N., Tsafrakidou P., Kornaros M., (2018). Bio-based products from microalgae cultivated in digestates. *Trends in Biotechnology*, 36(8): 819-833.
45. Kumar V., Arora N., Pandey S., Jaiswal K.K., Nanda M., Vlaskin M.S., Chauhan P.K. (2020). Microwave-assisted pre-treatment of harmful algal blooms for microbial oil-centered bio-refinery approach. Biomass Conversion and Biorefinery. https://doi.org/10.1007/s13399-020-00941-5
46. Lafarga T. (2020). Cultured microalgae and compounds derived thereof for food applications: Strain selection and cultivation, drying, and processing strategies. *Food Reviews International*, 36(6): 559-583.
47. Lin Z., Xu Y., Zhen Z., Fu Y., Liu Y., Li W., Luo C., Ding A., Zhang D., (2015). Application and reactivation of magnetic nanoparticles in *Microcystisaeruginosa* harvesting. *Bioresour. Technol.*, 190: 82–88. https://doi.org/10.1016/J.BIORTECH.2015.04.068.
48. Mata T.M., Martins, A.A., Caetano, N.S. (2010). Microalgae for biodiesel production and other applications: a review. *Renewable and Sustainable Energy Reviews*, 14(1): 217-232.
49. Mikulčić H., Skov I.R., Dominković D.F., Alwi S.R.W., Manan Z.A., Tan R., Wang X., (2019). Flexible Carbon Capture and Utilization technologies in future energy systems and the utilization pathways of captured CO_2. *Renewable and Sustainable Energy Reviews*, 114: 109338.
50. Padrova K., Lukavsky J., Nedbalova L., Čejkova A., Cajthaml T., Sigler K., Vitova M., Rezanka T., (2015). Trace concentrations of iron nanoparticles cause overproduction of biomass and lipids during cultivation of cyanobacteria and microalgae. *J. Appl. Phycol*., 27: 1443–1451. https://doi.org/10.1007/s10811-014-0477-1.
51. Radzun K.A., Wolf J., Jakob G., Zhang E., Stephens E., Ross I., Hankamer B., (2015). Automated nutrient screening system enables high-throughput optimisation of microalgae production conditions. *Biotechnol. Biofuels,* 8: 65. https://doi.org/10.1186/s13068-015-0238-7.
52. Rahman F.A., Aziz M.M.A., Saidur R., Bakar W.A.W.A., Hainin M.R., Putrajaya R., Hassan N.A., (2017). Pollution to solution: Capture and sequestration of carbon dioxide (CO_2) and its utilization as a renewable energy source for a sustainable future. *Renewable and Sustainable Energy Reviews*, 71: 112-126.
53. Razzak S.A., Hossain M.M., Lucky R.A., Bassi A.S., de Lasa H. (2013). Integrated CO_2 capture, wastewater treatment and biofuel production by microalgae culturing—a review. *Renewable and Sustainable Energy Reviews*, 27: 622-653.
54. Sankaran R., Show P.L., Nagarajan, D., Chang J.S., (2018).Exploitation and biorefinery of microalgae. In: Waste Biorefinery (pp. 571-601). Elsevier.
55. Saratale R.G., Kumar G., Banu R., Xia A., Periyasamy S., Saratale G.D., (2018). A critical review on anaerobic digestion of microalgae and macroalgae and co-digestion of biomass for enhanced methane generation. *BioresourceTechnology*, 262: 319-332.
56. Show P.L., Tang M.S., Nagarajan D., Ling T.C., Ooi, C.W., Chang, J.S. (2017). A holistic approach to managing microalgae for biofuel applications. *International Journal of Molecular Sciences*, 18(1): 215.

57. Singh U.B., Ahluwalia A.S., (2013). Microalgae: a promising tool for carbon sequestration. *Mitigation and Adaptation Strategies for Global Change*, 18(1): 73-95.
58. Slade R., Bauen A., (2013). Micro-algae cultivation for biofuels: cost, energy balance, environmental impacts and future prospects. *Biomass Bioenergy*, 53:29–38. https://doi.org/10.1016/J.BIOMBIOE.2012.12.019.
59. Sudhakar S., Jaiswal K.K., GousePeera S., Ramaswamy A.P., (2017). Green synthesis of N-graphene by hydrothermal-microwave irradiation for alkaline fuel cell application. *International Journal of Recent Scientific Research*, 8 (8): 19049-19053. http://dx.doi.org/10.24327/ijrsr.2017.0808.0619
60. Sudhakar S., Jaiswal K.K, Ramaswamy A.P., (2018). The Role of Microwave Irradiation Temperature on Nitrogen Doping in Metal-Free Graphene Catalysts for an Efficient Oxygen Reduction Reaction in an Alkaline Condition. *ChemistrySelect*, 3 (31): 8962-8972. https://doi.org/10.1002/slct.201801353
61. Syafaini-Japar A., Azis N.M., SobriTakriff M., Haiza N., Yasin M., (2017). Application of different techniques to harvest microalgae. *Trans. Sci. Technol.*, 4: 98–108.
62. Toichi T., (2012). Balance Between Energy Security and Mitigation Responses.In: Climate Change Mitigation. pp. 63-87. Springer, London.
63. Van Aalst M.K., (2006). The impacts of climate change on the risk of natural disasters. *Disasters*, 30 (1): 5-18.
64. Wang H.M.D., Chen C.C., Huynh P., (2015). Exploring the potential of using algae in cosmetics. *Bioresour. Technol.*, 184: 355–362. https://doi.org/10.1016/J.BIORTECH.2014.12.001.
65. Wang B., Li Y., Wu N., Lan C.Q. (2008). CO_2 bio-mitigation using microalgae. *Applied Microbiology and Biotechnology*, 79(5): 707-718.
66. Windt De W., Aelterman P., Verstraete W., (2005). Bioreductive deposition of palladium (0) nanoparticles on *Shewanellaoneidensis* with catalytic activity towards reductive dechlorination of polychlorinated biphenyls. *Environ. Microbiol.*, 7: 314–325. https://doi.org/10.1111/j.1462-2920.2005.00696.x.
67. Xu L., Guo C., Wang F., Zheng S., Liu C.Z., (2011). A simple and rapid harvesting method for microalgae by in situ magnetic separation. *Bioresour.Technol.*, 102: 10047–10051. https://doi.org/10.1016/J.BIORTECH.2011.08.021.
68. Yadav G., Sen R. (2017). Microalgal green refinery concept for biosequestration of carbon-dioxide vis-à-vis wastewater remediation and bioenergy production: Recent technological advances in climate research. *Journal of CO_2 Utilization*, 17:188-206.
69. Yamasaki A. (2003). An overview of CO_2 mitigation options for global warming—emphasizing CO_2 sequestration options. *Journal of chemical engineering of Japan*, 36(4): 361-375.
70. Yang Y., Hou J., Wang P., Wang C., Miao L., Ao Y., Xu Y., Wang X., Lv B., You G., Yang Z., (2018). Interpretation of the disparity in harvesting efficiency of different types of *Microcystisaeruginosa* using polyethylenimine (PEI)-coated magnetic nanoparticles. *Algal Res.*, 29: 257–265. https://doi.org/10.1016/J.ALGAL.2017.10.020.
71. Zhou W., Wang J., Chen P., Ji C., Kang Q., Lu B., Ruan R. (2017). Bio-mitigation of carbon dioxide using microalgal systems: advances and perspectives. *Renewable and Sustainable Energy Reviews*, 76: 1163-1175.
72. Zhu L.D., Hiltunen E., Li Z., (2017). Using magnetic materials to harvest microalgal biomass: evaluation of harvesting and detachment efficiency. *Environ. Technol.*, 1–7. https://doi.org/10.1080/09593330.2017.1415379.

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