**Microalgae- A promising tool for sustainable future**

Nilamjyoti Kalita1\*, Soumin Nath1,2, Trideep Chetia1,3, Bishmita Boruah1 and Partha Pratim Baruah1

1Plant Ecology Laboratory, Department of Botany, Gauhati University, Assam-781014, India

2 Dudhnoi College, Dudhnoi, Goalpara, Assam-783124, India

3Morigaon College, Morigaon, Assam-782105, India

\*Email: [nilamjyotikalita2014@gmail.com](mailto:nilamjyotikalita2014@gmail.com) (NK), [ppbaruah@gauhati.ac.in](mailto:ppbaruah@gauhati.ac.in) (PPB)

**Abstract**

With the world directing towards accomplishing the Sustainable Development Goals (SDGs) under the United Nations 2030 agenda to protect the planet and improve lives and prospects of everyone, everywhere, biological entities are being explored extensively to achieve them. While studies of microalgal applications for sustainable development have been carried out in the past, their interest have been rising in every sector including remediation of environment, food and fodder production, pharmaceuticals, cosmetics, biofertilizers, plastic degradation, bioplastic production and even biofuel production. These are organisms capable of performing photosynthesis and are found in various terrestrial to aquatic including marine habitats**.** Theability of microalgae to consume CO2 and produce a wide range of active compounds such as carbohydrates, lipids, proteins, pigments, vitamins, fatty acids, polysaccharides and antioxidants has led to their increasing implication as a tool for a sustainable future. This article discusses the prospects of application of micro algae, present trends and futuristic approach capable of leading towards a better environment and a sound future.

**Key words:** Microalgae, Bio prospects, Bibliometric analysis, VOS viewer software.

1. **Introduction**

Algae are a diverse group of autotrophic photosynthetic organisms, which are among the primary producers in the aquatic ecosystems capable of fixing CO2 into carbohydrates during photosynthesis (Haddad *et al*., 2014**).**They may be simple unicellular microscopic motile or non-motile, to complex branched macroscopic forms. Algae are ubiquitous in distribution and can be found in every possible habitat including marine and fresh water bodies (Desikachary, 1959). From 30,000 to over 1 million algal species are thought to exist in this world playing a vital role in functioning of both freshwater and marine ecosystems (Guiry, 2012). Among which, microalgae are the most diverse algal group existing in a broad variety of forms, sizes and shapes.

Despite being microscopic, the broad adaptability and potential advantages of microalgae have led to their surge in recent years in the field of research and sustainable development.  Being cosmopolitan, these microorganisms are excellent for investigation by ecologists, phycologists, biochemists, microbiologists as well as bacteriologists. Researchers are constantly looking for new beneficial applications of these microscopic organisms to develop novel technology and harness their potential for a healthier and better sustainable future.

Keeping the ideas above in mind this communication deals with all the aspects related to microalgal bio prospects and its potential scope in the near future through VOS (Visualization of Similarities) viewer software.

1. **Bio prospects of microalgae: past, present and future**

As a result of their numerous inherent benefits, algae have recently attracted a lot of attention for bioprospecting (Teronpi and Baruah 2017). Algae are one of the primary natural suppliers of a wide variety of beneficial substances, including antibiotics, proteins, carbohydrates, lipids, chlorophylls, carotenoids, phycobilins, glycolipids, phenolics, terpenes, β-diketone, polyols and indole alkaloids (Pratt *et al*., 1944; Ördög *et al*., 2004; Del Campo *et al*., 2007; Subudhi, 2017; Karkala *et al*., 2021). For which algae are being widely used in fish and animal feedstock, agricultural industry, neutraceutical and pharmaceutical industry, cosmetic industry and also are considered for biofertilizer, bio plastic and biodiesel production for sustainable environmental management (Fig 1) (Apt and Bahrens, 1999; Soletto *et al*., 2005; Spolaore *et al*., 2006; Milledge, 2011; De Jesus *et al*., 2013: Mullue *et al*., 2023). Algal species belonging to the genera *Anabaena*, *Nostoc*, *Botryococus*, *Chlamydomonas*, *Chlorella*, *Haematococcus*, *Scenedesmus*, have been well known source of vitamin precursors, antioxidants, immune system boosters, anti-inflammatory agents, beta-carotene, lutein, astaxanthin and polyunsaturated fatty acids and have already been utilized for production of commercial products (Stranska-Zachariasova *et al*., 2016; Mullue *et al*., 2023).

Microalgae have also been known to produce various metabolites showing antiviral and antifungal properties. Lectin cyanovirin-N, isolated from the cyanobacterium *Nostoc ellipsosporum*, has shown antiviral action against the ebola, influenza, and HIV viruses (Mullue *et al*., 2023). Astaxanthin is another potent antioxidant extracted from the green alga *Haematococcus pluvialis* (Plaza *et al*., 2009). Short chain fatty acids extracted from *Haematococcus pluvialis* have also presented strong antibacterial property against *Vibrio* strains (Subudhi, 2017). Green microalgal genus *Chlorella* produces chlorellin, an antibacterial substance that can prevent the growth of both Gram-positive and Gram-negative bacteria (Little *et al*., 2021). Chlorellinhas been extracted from the algal species *Chlorella vulgaris*. Calothrix A, an alkaloid isolated from the cyanobacteria *Calothrix*, has demonstrated to possess antibacterial property against *Bacillus subtilis* (Doan *et al*., 2001). *Spirulina* and *Chlorella vulgaris* are primarily used and exploited in the market for the manufacture of Single Cell Proteins (SCP) (Karkala *et al*., 2021). The green alga *Botryococcus braunii* produces allopathic substances viz. mixture of free fatty acids containing α-linolenic, oleic, linoleic, and palmitic acids. These fatty acids can become hazardous to other group of phytoplanktons, facilitating its dominance in the habitat (Bacellar-Mendes and Vermelho 2013). *Scytonema*, a cyanobacterial genus can be exploited for production of cyanobacterin, a chlorinated γ-lactone that specifically inhibits a variety of microalgae, including cyanobacteria and green algae, at micromolar concentrations (Mason *et al*., 1982).

For many industrial uses, microalgae-based biofuelshave been acknowledged as a feasible substitute for fossil fuels (Gong and Jiang, 2011). Researchers recommend that microalgae *Botryococcus braunii* and *Scenedesmus dimorphus* can be used as raw materials for production of biofuels (Nagaraja *et al*., 2014; Arone Sou raj *et al*., 2016; Tasic *et al*., 2016; Prathima and Karthikeyan 2017; Dilia *et al*., 2018). It has also been demonstrated that *Botryococcus braunii* is a potential candidate for bioremediation of domestic waste water as it can reduce ammonia, potassium, electrical conductivity and TDS from waste water (Arone Sou raj *et al*., 2016).



**Fig 1: Bio prospects of microalgae in different aspects**

1. **Recent trends of micro algal application**
   1. **Heavy metal (HM) remediation**

Microalgae are found to grow in harsh environment and they adsorb the noxious substances available therein. One of the toxic elements present in such environment is the HMs like cadmium (Cd), arsenic (As), lead (Pb), mercury (Hg), zinc (Zn), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni), chromium (Cr) etc. which are increasing in nature day by day (Kalita and Baruah, 2023).These HMs effects the aquatic and land ecosystem by incorporating in the food web.

Microalgae are the eco-friendly tools to remediate these harmful substances for a better and healthier future. Microalgal members like *Oscillatoria princeps* (Sulaymon *et al*., 2013), *Spirulina maxima* (Gong *et al*., 2005), *Aulosira fertilissima* (Singh *et al*., 2007), *Chlorella vulgaris* (Sandau *et al*., 1996; Klimmek *et al*., 2001; Ferreira *et al*., 2011)*, Scenedesmus obliquus* (Monteiro *et al*., 2011), *Microcystis* sp. (Singh *et al*., 1998), *Pithophora odeogonia* (Singh *et al*., 2007), *Spirogyra hyaline* (Kumar and Oommen, 2012)couldremove a number of toxic heavy metals from the environment in a variable pH and temperature ranges (Kumar et al., 2015). They possess a number of functional groups in their cell wall that are known to be involved in the metal uptake process (Kalita and Baruah, 2023). Electrostatic interaction between metal ions and the respective functional groups is critical for successful metal homeostasis. Once the metal ions are adsorbed onto the cell surface the live cells thereby activate the metabolically dependent active processes and transport the ions into the cell organelles. Mitochondria, chloroplast, vacuoles and poly p bodies are the organelles that are specifically involved in active transport during metal accumulation; while the non-living microalgal biomass are restricted to only adsorption mechanism.

* 1. **Biofuel Production**

Microalgae are abundant in lipids content and can be used to make biofuels like biodiesel, which are more eco-friendly substitutes for fossil fuels (Teronpi *et al*., 2021). Particularly,Triglyceride content in microalgae is the main source for the production of biofuel. On the other hand, biomass can be thermochemically transformed into biofuel oil (Lestari *et al*., 2009). Production of biofuel from microalgae has the potential to lower greenhouse gas emissions and lessen reliance on limited fossil fuel supplies. Among all the members of the microalgal group, chlorophycean members are rich in lipid content (Patidar *et al*., 2015) and it could be attributed to the production of biofuels. *Chlorella emersonii, Chlorella protothecoides, Schizochytrium limacinum, Scenedesmus obliquus* are the few members of chlorophycean members which are known for their rich lipid content (Suali and Sarbatly, 2012).

* 1. **Plastic degradation**

In general, plastics are regarded as synthetic or semi-synthetic materials or polymers, which although easy to use, but pose a threat to the environment. Conventional plastics affect the environment because they are produced from crude oil, a finite natural resource and do not decompose through bacterial decomposition, landfills merely store them for decades; and their combustion emits poisonous chemicals (Abdo and Ali, 2019). PVC (polyvinyl chloride), PE (polyethylene),  PP (Polypropylene), PET (Polyethylene Terephthalate ), LDPE (Low-Density Polyethylene), HDPE (High Density Polyethylene) are the most commonly used plastic compound in recent years.

Researchers have introduced a number of microbes including a few microalgae for the degradation of this polymeric substance. Algal species like *[Scenedesmus](https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/scenedesmus" \o "Learn more about Scenedesmus from ScienceDirect's AI-generated Topic Pages)* dimorphus, *Oscillatoria* subbrevis, *[Phormidium](https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/phormidium" \o "Learn more about Phormidium from ScienceDirect's AI-generated Topic Pages)* lucidum, *[Navicula](https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/navicula" \o "Learn more about Navicula from ScienceDirect's AI-generated Topic Pages)* pupula and *Anabaena spiroides*   are known to degrade PE (Sarma and Rout, 2019). Amongst those aforementioned species [*Anabaena spiroides*](https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/anabaena-spiroides), *[Scenedesmus](https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/scenedesmus" \o "Learn more about Scenedesmus from ScienceDirect's AI-generated Topic Pages)* dimorphus, *[Navicula](https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/navicula" \o "Learn more about Navicula from ScienceDirect's AI-generated Topic Pages)* pupula are known to degrade both HDPE and LDPE. Recently, Nostoc carneum has gained attention for the degradation mechanism of LDPE (Sarma and Rout, 2020).

* 1. **Bio plastic production**

Plant-based components such as naturally occurring polymers (carbohydrates, proteins, etc.), along with other tiny particles (sugar, disaccharides, and fatty acids) can be utilized to make bioplastics. Bioplastics capacity arose from roughly 2 million tons in 2014 to approximately 6.7 million tons in 2018, with the majority of them being manufactured from starch and poly (lactic acid) (PLA) based polymers.

In order to reduce the plastic pollution researchers have developed bioplastics from different natural sources including microalgae. Certain microalgae species have the potential to replace the synthetic polymers with biodegradable bioplastics as an ecofriendly substance. Microalgae are rich in carbohydrate and protein content, which serve as a core agent for production of bioplastics (Chia *et al*., 2020). Cellulose, Starch, PE, PVC, PHA (Polyhydroxyalkanoates), PHB (Polyhydroxybutyrate ), PLA and polymers based on protein are a few examples of chemicals from algal biomass that are being used to create biodegradable plastics. PHA is the polymer that is most frequently suggested for use in the production of bioplastics since it can be broken down by enzymatic action. Additionally, PHB, a subtype of PHA, has recently become a novel polymer for the production of bioplastics due to its effective oxygen barrier (Karan *et al*., 2019).

**3.5. Bio fertilizer**

A number of micro-organisms, plants and animals are known to the researchers and farmers that can be used as fertilizers as an alternative to chemical fertilizers (DasGupta *et al*., 2021). Microalgae can be used as a biofertilizers because of their ability to fix atmospheric nitrogen, boost soil fertility and promote plant growth and development. Certain microalgae, such as cyanobacteria, have the potential to fix atmospheric nitrogen into ammonia (Mishra and Pabbi, 2014), which is easily available to plants and could absorb very quickly and eventually help in plant growth and development. *Nostoc* sp., *Anabaena* sp., *Spirulina* *platensis* are known members of cyanobacteria which has gained attention for their high nitrogen fixing capacity. In such mechanism heterocyst (an organelles in cyanobacteria) solely play the key role in ammonia synthesis and nitrogen fixation (R. Banemann, 1979). In recent years a few chlorophyean members like *Chlorella* *vulgaris, Acutodesmus dimorphus* also known for their effective results in growth and development in many occassions (Gomiero *et al.* 2011; Kim *et al*., 2014; Bumandalai *et al*., 2019).

Apart from this, microalgae are known for their high content of trace elements, including phosphorous and calcium contents which enhance soil fertility. The organic elements also increase the water-holding capacity and augment soil building and health. The presence of active compounds such as phytohormones like auxin, cytokinins, and gibberellins and the occurrence of few antimicrobial properties make them suitable biofertilizers (Alvarez *et al*., 2021). Phytohormones such as indole 3-acetic acid, Indole butyric acid, Indole-3-propionic acid, Zeatin, and kinetin have been reported from various members of microalgae viz. *Nostoc* spp., *Anabaena* spp., *Aphanothece* sp. 515 MBDU, *Scenedesmus* *armatus*, *Chlorella* *pyrenoidosa***,** and *Scenedesmus obliquus* (Renuka *et al*., 2018). Therefore, it can be remarked that the use of such microalgae in crop fields shall enhance crop productivity and yield.

**3.6. Food and Fodder**

For thousands of years, algae have been a part of human diet across various regions of the globe (Aaronson, S. 1986). While these algae are mostly macroalgae such as *Porphyra, Gracilaria, Palmaria palmata, Lamina japonica, Ulva lactuca, Codium* etc., various micro algae have also found their way into human diet including *Spirulina spp., Nostoc commune, Chlorella spp., Dunaliella salina and Haematococcus pluvialis* (Borowitzka, 1998; Baruah *et al*., 2014; Wu *et al*., 2022).These algae are eaten fresh, dried, pickled as well as in backed forms with delight. Loaded with compounds such as carotenoids, amino acids, vitamins, antioxidants, lipids, fatty acids and carbohydrates etc., algae are being used today in food industries extensively as food supplements (Wells *et al*., 2016). Algae have also been used to enrich meat products, fish products, cereal products and produce fermented products (Ścieszka and Klewicka, 2018, Hung *et al*., 2021).

As a feed source, microalgae have been used in hatchery for farmed shellfish, finfish as well as other species grown commercially. Algal species are cultivated separately and regularly administered into these aquacultures (Shields and Lupatsch, 2012). Numerous studies have been carried out to study the application of various algal stains, their nutritional composition, techniques of their cultivation as well as methods of delivery for their efficiency (Brown *et al*. 1997, Muller-Feuga *et al*., 2003). *Nannochloropsis*, *Skeletonema costatum*, *Navicula*, *Nitzschia*, *Chlorella* spp., *Dunaliella* spp. are some major microalgal species used in aquaculture (Shields and Lupatsch, 2012; Nagappan, 2021). Application of algal as feed for animals has been correlated to development of overall healthy animal physiology by lowering cholesterol, boosting immunity, improving gut functioning, increasing quality milk production as well as meat and egg quality (Liu *et al*., 2013; Suresh *et al*., 2017; Costa *et al*., 2022). *Dunaliella salina*, *Nannochloropsis granulate*, *Tetraselmis chui*, *Phaeodactulum*, *Scenedesmus* and *Chlorella* are some commonly used feeds for livestocks (Shields and Lupatsch, 2012; Saadaoui, 2021; Costa *et al*., 2022)

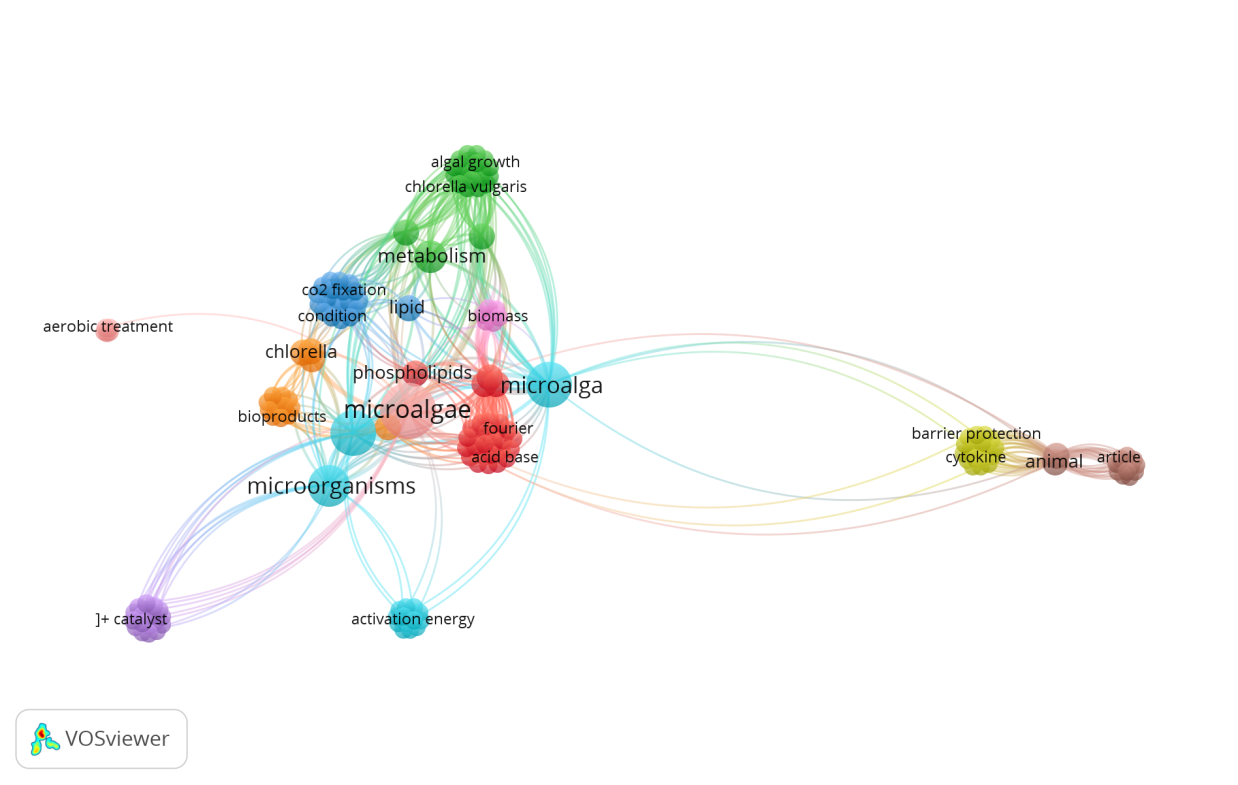
**Table1: Algal species with their potent role in emerging areas of bios prospects**

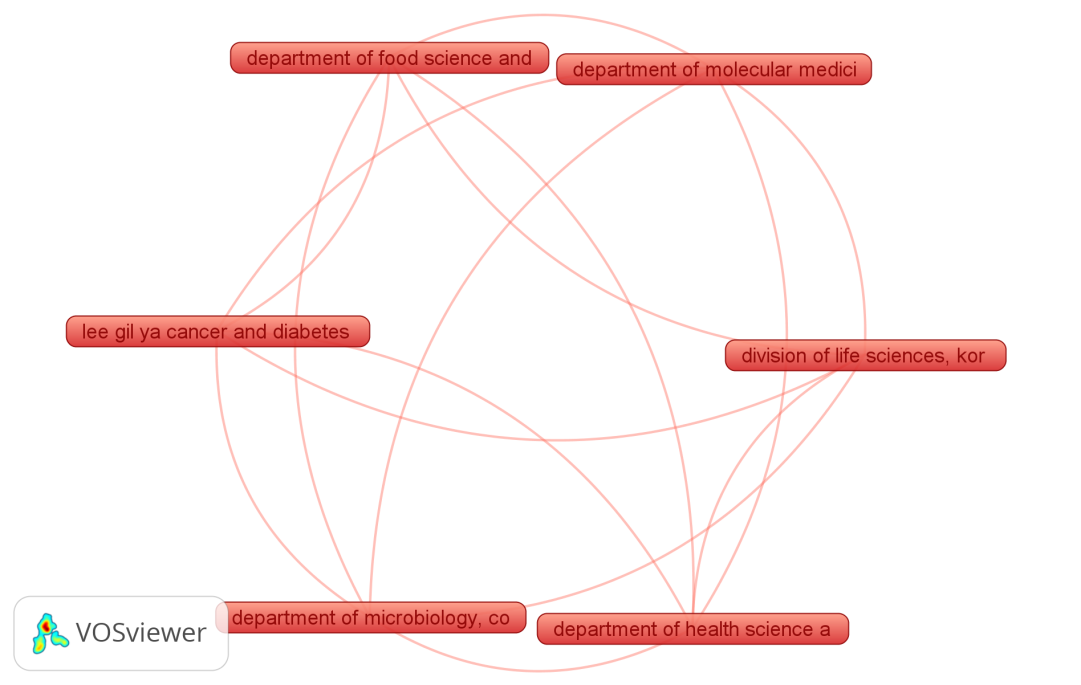
|  |  |  |  |
| --- | --- | --- | --- |
| **Name of the species** | **Algal group** | **Uses** | **References** |
| *Acutodesmus dimorphus* | Green alga | Biofertilizer | Gonzalez and Sommerfeld (2016) |
| *Anabaena oryzae* | Cyanobacteria | HM (Cu, Zn) removal | El-Bestawy (2008) |
| *Anabaena* sp. | Cyanobacteria | Biofertilizer | Chittora *et al.* (2020) |
| *Anabaena spiroides* | Cyanobacteria | Plastic degradation | Kumar *et al.* (2017) |
| *Anabaena variabilis* | Cyanobacteria | HM (Cd) removal | El-Hameed *et al.* (2021) |
| *Aphanizomenon flos‐aquae* | Cyanobacteria | Food | Kay and Barton, (2009) |
| *Arthrospira platensis* | Cyanobacteria | Food | Kejzar (2021); Aljobair (2021) |
| *Arthrospira* sp. | Cyanobacteria | Bioplastic production | Arora *et al.* (2023) |
| *Aulosira fertilissima* | Cyanobacteria | HM (Cd, Pb, Cu, Zn, Ni) removal | Singh *et al.* (2007) |
| *Calothrix marchica* | Cyanobacteria | HM (Cd, Hg, Pb) removal | Inthorn *et al.* (2002) |
| *Chlamydomonas reinhardtii* | Green alga | HM (Co, Cd) removal | Macfie and welbourn (2000) |
| *Chlorella vulgaris* | Green alga | HM (Ni) removal | Mehta and Gaur (2001) |
| *Chlorella vulgaris* | Green alga | Plastic degradation | Falah *et al.* (1964) |
| *Chlorella vulgaris* | Green alga | Biofertilizer | Dineshkumar *et al.* (2017) |
| [*Chlorella pyrenoidosa*](https://www.sciencedirect.com/science/article/pii/S221478531831126X) | Green alga | Biofuel production | Das *et al.* (2018) |
| [*Chlorella pyrenoidosa*](https://www.sciencedirect.com/science/article/pii/S221478531831126X) | Green alga | Bioplastic production | Das *et al.* (2018) |
| Chlorella sp. | Green alga | Food | Spolaore *et al.* (2006), Kay and Barton, (2009) |
| *Chlorella vulgaris* | Green alga | Bioplastic production | Selvaraj *et al.* (2021) |
| *Chlorococcum humicola* | Green alga | Antimicrobial activity | Bhagavathy *et al.* (2011) |
| Chlorococcum sp. | Green alga | Biofertilizer | Deepika and MubarakAli, (2020) |
| *Dolichospermum crassum* | Cyanobacteria | Anticancer activity against prostrate and colon cancer | Senousy *et al.* (2020) |
| Dolichospermum spiroides | Cyanobacteria | Anticancer activity against hepatic cancer | Senousy *et al.* (2020) |
| Dunaliella  sp. | Green alga | Food | Spolaore *et al.* (2006) |
| *Hapalosiphon hibernicus* | Cyanobacteria | HM (Cd, Hg, Pb) removal | Inthorn *et al.* (2002) |
| *Mastagocladus* sp*.* | Cyanobacteria | HM (Cd, Hg, Pb) removal | Inthorn *et al.* (2002) |
| *Microcystis aeruginosa MKR 0105* | Cyanobacteria | Biofertilizer | Grzesik *et al.* (2017) |
| *Nannochloropsis* sp. | Green alga | Biofuel | Wang and wang, (2012) |
| *Nostoc carneum* | Cyanobacteria | Plastic degradation | Sarmah and Rout, (2019) |
| *Nostoc linckia* | Cyanobacteria | HM (Cr,Cu,Fe,Ni,Zn) removal | Cepoi *et al.* ( 2021) |
| *Nostoc muscorum* | Cyanobacteria | Bioplastic production | Arora *et al.* (2023) |
| Nostoc muscorum . | Cyanobacteria | Anticancer activity | Shanab *et al.* (2012) |
| *Nostoc* sp. | Cyanobacteria | biofertilizer | Chittora *et al.* (2020) |
| Oscillatoria sancta | Cyanobacteria | Anticancer activity against breast cancer | Senousy *et al.* (2020) |
| Oscillatoria sp. | Cyanobacteria | Anticancer activity | Shanab *et al.* (2012) |
| *Scenedesmus dimorphus* | Green alga | Plastic degradation | Kumar *et al.* ( 2017) |
| *Scenedesmus obliquus* | Green alga | HM (Cd) removal | Monteiro *et al.* (2009) |
| *Scenedesmus obliquus* | Green alga | Food | Hlaing (2020) |
| *Scenedesmus* sp. | Green alga | Food | Kay and Barton, (2009) |
| *Schizochytrium* sp. | Green alga | Biofuel | Wang and wang, 2012 |
| *Spirulina platensis* | Cyanobacteria | Food | Marzieh Hosseini *et al.* (2013) |
| *Spirulina platensis* | Cyanobacteria | HM (Co, Cu, Zn) removal | Vannela and verma, (2006) |
| *Spirulina platensis* | Cyanobacteria | Biofertilizer | Dineshkumar *et al.* (2017) |
| *Synecchococcus* sp*.* | Cyanobacteria | HM (Pb, Cd, Cr, Ni) removal | Gardea-Torresdey *et al.* (1998) |
| *Synechococcus* sp. MA19. | Cyanobacteria | Bioplastic production | Arora *et al.* (2023) |
| *Synechocystis* PCC6803 | Cyanobacteria | Bioplastic production | Arora *et al.* (2023) |
| *Tolypothrix tenuis* | Cyanobacteria | HM (Cd, Hg, Pb) removal | Inthorn *et al.* (2002) |
| *Westiellopsis prolifica* | Cyanobacteria | Biofertilizer | Dutta and Baruah (2020) |

1. **Research trend and futuristic approach**

Bibliometric analysis is the common and thorough method for studying and analysing vast amounts of scientific data (Donthu *et al.*, 2021). It allows for the enhancement of research ideas and trends in particular topics for greater knowledge. Bibliometric analysis of “Microalgae” research using the data collected on 11th August 2023 from Scopus database revealed a total of 23,904 research articles were visualized through documented forms which are limited to only “Article”, “Microalgae’, “Microalga”, “Algae” and “Microorganisms”. Interestingly, the analysis of keywords shows that the most frequently used keywords in this aspects are “Microalgae/Microalga” and “Microorganisms” followed by “*Chlorella*”, “Phospholipids”, “Lipids”, “Metabolism”, “Bioproducts” and “Aerobic treatment”. The graphical representation in Figure 2 is the keywords cluster arranged in network form for better visualization. The information gathered through this network revealed that among the 23,904 documents of microalga, *Chlorella vulgaris* is the most explored species which could have the highest prospects toward lipid extraction and aerobic treatment process. Thus, we could understand that *Chlorella vulgaris* could be a better agent in all aspects.

On the other stance Figure, 3 data showed that “Department of food science and Biotechnology, Gachon University”, “Department of health science and Technology, Gachon advanced institute for health sciences and Technology”, “Department of Microbiology, College of Medicine, Gachon University”, Department of molecular medicine, College of Medicine, Gachon University”, “Division of life science, Korea polar research institute, South Korea” and “Lee gil ya cancer and diabetes institute, Gachon University” are the organization related to Co-authorship of research in the field of microalgae. The information could indicate that there are many scopes in microalgal research in the aspects that are not dealt with for other microalgal members.



**Fig 2: Network analysis of keywords**

**Fig 3: Network analysis of co authorship of organizations in microalgae**

1. **Conclusion**

Even while microalgae exhibit enormous promising features, there are still issues to be solved, including identification of a greater number of potential species for industrial uses, improving cultivation methods to produce higher amount of biomass and ensuring economic sustainability. In spite of these, continued research and technological development are steadily enhancing microalgae's bio prospects and broadening their range of industrial use which in turn will lead to a better and sustainable future.

**Author contributions**

NK: Investigation, visualization, software, writing-original draft, editing; SN: Visualization, writing-original draft; TC: Writing-original draft, editing*;* BB:Writing-original draft; PPB: Supervision, investigation, visualization, writing- reviewing & editing.

**Acknowledgement**

Authors are grateful to Head, Department of Botany, Gauhati University for providing facilities developed under DST-FIST, UGC-SAP, OIL, MoEF & CC, ASTEC for rendering help to carry out the research work.

**References**

Aaronson, S. (1986). A role for algae as human food in antiquity. *Foodways*. 1, 311–315.

Abdo, S. M. & Ali, G. H. (2019). Analysis of polyhydroxybutrate and bioplastic production from microalgae. *Bulletin of the National Research Centre*, *43*(1), 1-4.

Alvarez, A. L., Weyers, S. L., Goemann, H. M., Peyton, B. M., & Gardner, R. D. (2021). Microalgae, soil and plants: A critical review of microalgae as renewable resources for agriculture. *Algal Research*, *54*, 102200.

Apt, K. E. & Behrens, P. W. (1999). Commercial developments in microalgal biotechnology. *J Phycol*. 35(2): 215-226.

Arone Soul Raj, G. P., Elumalai, S., Sangeetha, T., Singh, D. R. & Kanna, G. R. (2016). *Botryococcus braunii* as a potential candidate for the waste water treatment & hydrocarbon accumulation. *International Journal of Scientific & Engineering Research*. 7(6): 917-935.

Arora, Y., Sharma, S., & Sharma, V. (2023). Microalgae in Bioplastic Production: A Comprehensive Review. *Arabian Journal for Science and Engineering*, 1-17.

Bacellar Mendes, L. B., & Vermelho, A. B. (2013). Allelopathy as a potential strategy to improve microalgae cultivation. *Biotechnology for biofuels*, *6*(1), 1-14.

Baruah, P. P., Baruah, R., & Das, P. (2014). A preliminary study on diversity and distribution of *Spirulina*, *Arthrospira* and *Glaucospira* (Cyanobacteria) in the Brahmaputra Valley of Assam (India). *Feddes Repertorium*, *125*(3‐4), 85-92.

Bhagavathy, S., Sumathi, P., & Bell, I. J. S. (2011). Green algae *Chlorococcum* *humicola*-a new source of bioactive compounds with antimicrobial activity. *Asian Pacific Journal of Tropical Biomedicine*, *1*(1), S1-S7.

Borowitzka, M. A. (1998). Algae as food. *Microbiology of Fermented Foods*, 585–602.

Brown, M. R., Jeffrey, S. W., Volkman, J. K., & Dunstan, G. A. (1997). Nutritional properties of microalgae for Mariculture. *Aquaculture*, 151(1–4), 315–331.

Bumandalai, O., & Tserennadmid, R. (2019). Effect of *Chlorella* *vulgaris* as a biofertilizer on germination of tomato and cucumber seeds. *International Journal of Aquatic Biology*, *7*(2), 95-99.

Cepoi L, Zinicovscaia I, Chiriac T, Rudi L, Yushin N, Miscu V. (2019). Silver and gold ions recovery from batch systems using *Spirulina platensis* biomass. *Ecological Chemistry and Engineering* S. Jun 1;26(2):229-40.

Chia, W. Y., Tang, D. Y. Y., Khoo, K. S., Lup, A. N. K., & Chew, K. W. (2020). Nature’s fight against plastic pollution: Algae for plastic biodegradation and bioplastics production. *Environmental Science and Ecotechnology*, *4*, 100065.

Chittora, D., Meena, M., Barupal, T., Swapnil, P., & Sharma, K. (2020). Cyanobacteria as a source of biofertilizers for sustainable agriculture. *Biochemistry and biophysics reports*, *22*, 100737.

Costa, D. F., Castro-Montoya, J. M., Harper, K., Trevaskis, L., Jackson, E. L., & amp; Quigley, S. (2022). Algae as feedstuff for ruminants: A focus on single-cell species, opportunistic use of algal by-products and on-site production. *Microorganisms*, 10(12), 2313.

Das, S. K., Sathish, A., & Stanley, J. (2018). Production of biofuel and bioplastic from *Chlorella* *pyrenoidosa*. *Materials today: proceedings*, *5*(8), 16774-16781.

Dasgupta, D., Kumar, K., Miglani, R., Mishra, R., Panda, A. K., & Bisht, S. S. (2021). Microbial biofertilizers: Recent trends and future outlook. *Recent Advancement in Microbial Biotechnology*, 1-26.

De Jesus Raposo, M. F., de Morais, R. M. S. C. & de Morais, A. M. M. B. (2013). Bioactivity & applications of sulphated polysaccharides from marine microalgae. *Mar Drugs*. 11(1):233-252.

Deepika, P., & MubarakAli, D. (2020). Production and assessment of microalgal liquid fertilizer for the enhanced growth of four crop plants. *Biocatalysis and agricultural biotechnology*, *28*, 101701.

Del Campo, J. A., García-González, M. & Guerrero, M. G. (2007). Outdoor cultivation of microalgae for carotenoid production: current state & perspectives. *Appl Microbiol Biotechnol*. 74: 1163-1174.

Dilia, P., Leila, K., & Rusdianasari (2018). Fatty Acids From Microalgae *Botryococcus braunii* For Raw Material of Biodiesel. *Journal of Physics: Conf. Series*. 1095: 012010.

Dineshkumar, R., Subramanian, J., Gopalsamy, J., Jayasingam, P., Arumugam, A., Kannadasan, S., & Sampathkumar, P. (2019). The impact of using microalgae as biofertilizer in maize (Zea mays L.). *Waste and Biomass Valorization*, *10*, 1101-1110.

Doan, T. N., Rickards, R. W., Rothschild, J. M. & Smith, G. D. (2001). Inhibition of bacterial RNA polymerase by the cyanobacterial metabolites 12-epi-hapalindole E isonitrile & calothrixin A. *FEMS Microbiol Lett*. 196(2):135-139.

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W. M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. *Journal of business research*, *133*, 285-296.

Dutta, J., & Baruah, P. P. (2020). Evaluating differential effect of deltamethrin and carbofuran on growth characteristics of *Westiellopsis* *prolifica* Janet, a dominant nitrogen fixing cyanobacterium of tropical rice field ecosystem. *Biocatalysis and Agricultural Biotechnology*, *23*, 101490.

El-Bestawy, E. (2008). Treatment of mixed domestic–industrial wastewater using cyanobacteria. *Journal of Industrial Microbiology and Biotechnology*, *35*(11), 1503-1516.

El-Hameed, M. M. A., Abuarab, M. E., Al-Ansari, N., Mottaleb, S. A., Bakeer, G. A., Gyasi-Agyei, Y., & Mokhtar, A. (2021). Phycoremediation of contaminated water by cadmium (Cd) using two cyanobacterial strains (*Trichormus variabilis* and *Nostoc muscorum*). *Environmental Sciences Europe*, *33*(1), 1-10.

Falah, W., Chen, F. J., Zeb, B. S., Hayat, M. T., Mahmood, Q., Ebadi, A., ... & Li, E. Z. (2020). Polyethylene terephthalate degradation by microalga *Chlorella* *vulgaris* along with pretreatment. *Mater. Plast*, *57*(3), 260-270.

Ferreira, L. S., Rodrigues, M. S., Carlos, M.D.C.J., Alessandra, L., Elisabetta, F., Patrizia, P., Attilio, C., (2011). Adsorption of Ni2+, Zn2+ and Pb2+ onto dry biomass of *Arthrospira* (*Spirulina*) *platensis* and *Chlorella* *vulgaris*. I. Single metal systems. *Chem. Eng*. *J*. 173,326–333.

Garcia-Gonzalez, J., & Sommerfeld, M. (2016). Biofertilizer and biostimulant properties of the microalga *Acutodesmus* *dimorphus*. *Journal of applied phycology*, *28*, 1051-1061.

Gong, R., Ding, Y., Liu, H., Chen, Q., Liu, Z., (2005). Lead biosorption and desorption by intact and pretreated *Spirulina* *maxima* biomass. *Chemosphere* 58, 125–130.

Gong, Y. & Jiang, M. (2011). Biodiesel production with microalgae as feedstock: from strains to biodiesel. *Biotechnol Lett*. 33:1269-1284.

Grzesik, M., Romanowska-Duda, Z., & Kalaji, H. M. (2017). Effectiveness of cyanobacteria and green algae in enhancing the photosynthetic performance and growth of willow (Salix viminalis L.) plants under limited synthetic fertilizers application. *Photosynthetica*, *55*, 510-521.

Hung, L. D., Nguyen, H. T., & Trang, V. T. (2021). Kappa Carrageenan from the red alga *Kappaphycus* striatus cultivated at Vanphong Bay, Vietnam: Physicochemical properties and Structure. *Journal of Applied Phycology*, *33*(3), 1819–1824.

Inthorn, D., Sidtitoon, N., Silapanuntakul, S., & Incharoensakdi, A. (2002). Sorption of mercury, cadmium and lead by microalgae. *Sci Asia*, *28*(3), 253-261.

John R. Benemann, Production of nitrogen fertilizer with nitrogen-fixing blue - green algae, Enzyme and Microbial Technology, Volume 1, Issue 2, 1979, Pages 83-90, ISSN 0141-0229.

Kalita, N., & Baruah, P. P. (2023). Cyanobacteria as a potent platform for heavy metals biosorption: Uptake, responses and removal mechanisms. *Journal of Hazardous Materials Advances*, 100349.

Karan, H., Funk, C., Grabert, M., Oey, M., & Hankamer, B. (2019). Green bioplastics as part of a circular bioeconomy. *Trends in plant science*, *24*(3), 237-249.

Karkala, S., D’Souza, L. & Nivas, S. K. (2021). Bioprospecting microalgae harnessed from the coastal belt of Mangalore, India as prospective nutraceutical & biofuel candidates. *Applied Phycology*. 2(1): 60-73.

Kay, Robert A. & Barton, Larry L. (1991) Microalgae as food and supplement, *Critical Reviews in Food Science and Nutrition*, 30:6, 555-573

Kim, M. J., Shim, C. K., Kim, Y. K., Park, J. H., Hong, S. J., Ji, H. J., ... & Yoon, J. C. (2014). Effect of *Chlorella* *vulgaris* CHK0008 fertilization on enhancement of storage and freshness in organic strawberry and leaf vegetables. *Horticultural Science and Technology*, *32*(6), 872-878.

Klimmek, S., Stan, H.J., Wilke,A., Bunke,G., Buchholz,R., (2001).Comparative analysis of the biosorption of cadmium, lead, nickel and zinc by algae.*Environ.Sci.Technol*.35,4283–4288.

Kumar, R. V., Kanna, G. R., & Elumalai, S. (2017). Biodegradation of polyethylene by green photosynthetic microalgae. *J Bioremediat Biodegrad*, *8*(381), 2.

Kumar, J. I. N., Oommen, C., (2012). Removal of heavy metals by biosorption using freshwater alga *Spirogyra* *hyaline. J.Environ.Biol*.33,27–31.

Lestari, S., Mäki‐Arvela, P., Beltramini, J., Lu, G. M., & Murzin, D. Y. (2009). Transforming triglycerides and fatty acids into biofuels. *ChemSusChem: Chemistry & Sustainability Energy & Materials*, *2*(12), 1109-1119.

Lestari, S., Mäki‐Arvela, P., Beltramini, J., Lu, G. M., & Murzin, D. Y. (2009). Transforming triglycerides and fatty acids into biofuels. *Chem Sus Chem: Chemistry & Sustainability Energy & Materials*, *2*(12), 1109-1119.

Little, M. S., Senhorinho, G. N. A., Saleh, M., Basiliko, N. & Scott, J. A. (2021). Antibacterial compounds in green microalgae from extreme environments: a review. *Algae*. 36(1): 61-72.

Liu, J., Sommerfeld, M. & Hu, Q. (2013). Screening and characterization of *Isochrysis* strains and optimization of culture conditions for docosahexaenoic acid production. *Applied Microbiology and Biotechnology*. 97(11), 4785–4798.

Macfie, S.M.,Welbourn, P.M., (2000). The Cell Wall as a Barrier to Uptake of Metal Ions in the Unicellular Green Alga *Chlamydomonas reinhardtii* (Chlorophyceae). *Arch. Environ. Contam. Toxicol*. 39, 413–419.

Marzieh Hosseini, S., Shahbazizadeh, S., Khosravi-Darani, K., & Reza Mozafari, M. (2013). Spirulina paltensis: Food and function. *Current Nutrition & Food Science*, *9*(3), 189-193.

Mason, C. P., Edwards, K. R., Carlson, R. E., Pgnatello, J., Gleason, R. K., & Wood, J. M. (1982). Isolation of chlorine-containing antibiotic from the freshwater Cyanobacterium *Scytonema hofmanni*. *Science*. 213(4531):400-402.

Mehta, S.K., Gaur,J.P., (2005). Use of algae for removing heavy metal ions from wastewater: progress and prospects.*Crit.Rev.Biotechnol*.25,113–152.

Milledge, J. J. (2011). Commercial application of microalgae other than as biofuels: a brief review. *Rev Environ Sci Biotechnol*. 10: 31-41.

Mishra, U., & Pabbi, S. (2004). Cyanobacteria: a potential biofertilizer for rice. *Resonance*, *9*, 6-10.

Monteiro, C. M., Castro, P. M. L., Malcata, F. X., (2012).Metal uptake by microalgae: underlying mechanisms and practical applications. *Biotechnol. Prog*. 28(2), 299–311.

Monteiro, C. M., Castro, P. M. L., Malcata, F. X., (2011). Capacity of simultaneous removal of zinc and cadmium from contaminated media, by two microalgae isolated from a polluted site. *Environ. Chem. Lett*. 9(4),511–517.

Muller-Feuga, A., Robert, R., Cahu, C., Robin, J., & Divanach, P. (2003). Uses of microalgae in Aquaculture. *Live Feeds in Marine Aquaculture*, 253–299.

Mulluye, K., Bogale, Y., Bayle, D. & Atnafu, Y. (2023). Review on Microalgae Potential Innovative Biotechnological Applications. *Biosciences Biotechnology Research Asia*. 20(1): 35-43

Nagappan, S., Das, P., AbdulQuadir, M., Thaher, M., Khan, S., Mahata, C., Al-Jabri, H., Vatland, A. K. and Kumar, G. (2021). Potential of microalgae as a sustainable feed ingredient for aquaculture. *Journal of Biotechnology*, 341, 1–20.

Nagaraja, Y. P., Biradar, C., Manasa, K. S. & Venkatesh, H. S. (2014). Production of biofuel by using micro algae (*Botryococcus braunii*). *Int.J.Curr.Microbiol.App.Sci*. 3(4): 851-860.

Ördög, V., Stirk, W. A., Lenobel, R., Bancířová, M., Strnad, M., Van Staden, J., Szigeti, J. & Németh, L. (2004). Screening microalgae for some potentially useful agricultural & pharmaceutical secondary metabolites. *J. Appl. Phycol*. 16: 309-314.

Patidar, S. K., Mishra, S. K., Bhattacharya, S., Ghosh, T., Paliwal, C., Goel, S., & Mishra, S. (2015). Naturally floating microalgal mat for in situ bioremediation and potential for biofuel production. *Algal Research*, *9*, 275-282.

Plaza, M., Herrero, M., Cifuentes, A., Ibanez, E. (2009). Innovative natural functional ingredients from microalgae. *J Agric Food Chem*. 57(16): 7159-7170.

Prathima, A. & Karthikeyan, S. (2017). Characteristics of micro-algal biofuel from *Botryococcus braunii*. *Energy Sources, Part A: Recovery, Utilization, & Environmental Effects*. 39(2): 206-212.

Pratt, R., Daniels, T. C., Eiler, J. J., Gunnison, J. B., Kumler, W. D., Oneto, J. F., Strait, L. A., Spoehr, H. A., Hardin, G. J., Milner, H. W., Smith, J. H., & Strain, H. H. (1944). *Science*. 99(2574):351-352.

Renuka, N., Guldhe, A., Prasanna, R., Singh, P., & Bux, F. (2018). Microalgae as multi-functional options in modern agriculture: current trends, prospects and challenges. *Biotechnology advances*, *36*(4), 1255-1273.

Sandau, E.,Sandau,P.,Pulz,O.,Zimmermann,M.,(1996).Heavy metal sorption by marine algae and algal by-products*. Acta Biotechnol*.16(2–3), 103–119.

Saadaoui, I., Rasheed, R., Aguilar, A., Cherif, M., Al Jabri, H., Sayadi, S. & Manning, S. R. (2021). Microalgal-based feed: Promising alternative feedstocks for livestock and poultry production. Journal of Animal Science and Biotechnology, 12(1).

Sarmah, P., & Rout, J. (2019). Cyanobacterial degradation of low-density polyethylene (LDPE) by *Nostoc* *carneum* isolated from submerged polyethylene surface in domestic sewage water. *Energy, Ecology and Environment*, *4*, 240-252.

Sarmah, P., & Rout, J. (2020). Role of algae and cyanobacteria in bioremediation: prospects in polyethylene biodegradation. In *Advances in cyanobacterial biology* (pp. 333-349). Academic Press.

Ścieszka, S., & Klewicka, E. (2018). Algae in food: A general review. *Critical Reviews in Food Science and Nutrition*, *59*(21), 3538–3547.

Selvaraj, K.; Vishvanathan, N.; Dhandapani, R.: Screening, optimization and characterization of poly hydroxy butyrate from fresh water microalgal isolates. Int. J. Biobased Plast. 3(1), 139–162 (2021).

Senousy, H. H., Abd Ellatif, S., & Ali, S. (2020). Assessment of the antioxidant and anticancer potential of different isolated strains of cyanobacteria and microalgae from soil and agriculture drain water. *Environmental Science and Pollution Research*, *27*, 18463-18474.

Shanab SM, Mostafa SS, Shalaby EA, Mahmoud GI. (2012) Aqueous extracts of microalgae exhibit antioxidant and anticancer activities. *Asian Pac J Trop Biomed*. 2(8):608-15.

Shields, R., & Lupatsch, I. (2012). 5 algae for aquaculture and animal feeds. *Microalgal Biotechnology: Integration and Economy*, 79–100.

Singh, A., Mehta, S. K., Gaur, J. P. (2007). Removal of heavy metals from aqueous solution by common freshwater filamentous algae. *World J. Microbiol. Biotechnol*. 23, 1115–1120.

Singh, S., Pradhan, S., Rai, L. C., (1998). Comparative assessment of Fe3+ and Cu2+ biosorption by field and laboratory-grown *Microcystis*. *Process* *Biochem*.33(5), 495–504.

Soletto, D., Binaghi, L. & Lodi, A. (2005). Batch & fedbatch cultivations of *Spirulina* *platensis* using ammonium sulphate & urea as nitrogen sources. *Aquaculture*. 243(1-4): 217-224.

Spolaore, P., Joannis-Cassan, C., Duran, E. & Isambert, A. (2006). Commercial applications of microalgae. *J Biosci Bioeng*. 101: 87-96.

Spolaore, P., Joannis-Cassan, C., Duran, E., & Isambert, A. (2006). Commercial applications of microalgae. *Journal of bioscience and bioengineering*, *101*(2), 87-96.

Stranska-Zachariasova, M., Kastanek, P., Dzuman, Z., Rubert, J., Godula, M. & Hajslova, J. (2016). Bioprospecting of microalgae: Proper extraction followed by high performance liquid chromatographic-high resolution mass spectrometric fingerprinting as key tools for successful metabolom characterization. *J Chromatogr* *B*. 1015-1016: 22-23.

Suali, E., & Sarbatly, R. (2012). Conversion of microalgae to biofuel. *Renewable and Sustainable Energy Reviews*, *16*(6), 4316-4342.

Subudhi, S. (2017). Bioprospecting for Algal Based Nutraceuticals & High Value Added Compounds. *J Pharm Pharmaceutics*. 4(2): 145-150.

Sulaymon, A. H., Mohammed, A. A., & Al-Musawi, T. J. (2013). Competitive biosorption of lead, cadmium, copper, and arsenic ions using algae. *Environmental Science and Pollution Research*, *20*, 3011-3023.

Suresh, G., Das, R. K., Kaur Brar, S., Rouissi, T., Avalos Ramirez, A., Chorfi, Y. & Godbout, S. (2017). Alternatives to antibiotics in poultry feed: Molecular perspectives. *Critical Reviews in Microbiology*, 44(3), 318–335.

Tasić, M. B., Pinto, L. F. R., Klein, B. C., Veljković, V. B. & Filho, R. M. (2016). *Botryococcus braunii* for biodiesel production. *Renewable & Sustainable Energy Reviews*. 64: 260-270.

Teronpi, H. & Baruah, P. P (2017). Estimating lipids for bioprospecting: A case study with Deepor beel algae. *Annals of Plant Sciences*. 6(10): 1713-1717.

Teronpi, H., Baruah, P. P., & Deka, H. (2021). Salinity stress as a critical factor to trigger lipid accumulation in a freshwater microalga *Lobochlamys* sp. GUEco1006. *Biologia*, *76*(12), 3647-3658.

Wang, G., & Wang, T. (2012). Characterization of lipid components in two microalgae for biofuel application. *Journal of the American Oil Chemists' Society*, *89*(1), 135-143.

Wells, M. L., Potin, P., Craigie, J. S., Raven, J. A., Merchant, S. S., Helliwell, K. E., Smith, A. G., Camire, M. E., & Brawley, S. H. (2016). Algae as nutritional and functional food sources: Revisiting our understanding. *Journal of Applied Phycology*, *29*(2), 949–982.

Wu, G., Zhuang, D., Chew, K. W., Ling, T. C., Khoo, K. S., Van Quyen, D., Feng, S., & Show, P. L. (2022). Current status and future trends in removal, control, and mitigation of algae food safety risks for human consumption. *Molecules*, *27*(19), 6633.