**THIRD GENERATION BIOREFINERIES: AN APPROACH TOWARDS A SUSTAINABLE FUTURE**

**Abstract**

Microalgae are the broad range of photosynthetic autotrophs that are found both in fresh and marine water bodies worldwide. Microalgae are the known for producing value added products via the sequestration of carbon dioxide. This production is supported by other salient features like higher light conversion efficiency, higher substrate conversion efficiency, higher biomass productivities and shorter generation time. Microalgae biomass can be contemplated as a microbial cell factories that potentially biosynthesize wide range of value-added biomolecules like biopigments, therapeutic compounds, bioenergy, food, food supplements, animal feeds, biofertilizers and cosmetics etc. Sustainable industrial and biorefinery implications becomes feasible because of the multifaceted utility of microalgal biomass. The ultimate aim of a biorefinery is to sustainably transform biomass into a wide range of significant chemicals, fuels, and materials. Bio-renewables industry is empowered by third-generation (3G) biorefinery whose principal components are algal feedstock i.e., microalgae and macroalgae. Still, algal feedstock are the chief producers of pharmaceuticals, nutraceuticals and cosmetics.

**Key words** - Algal enzymes, industrial microbiology, enzyme production, biorefinery approach, sustainable bioprocess.

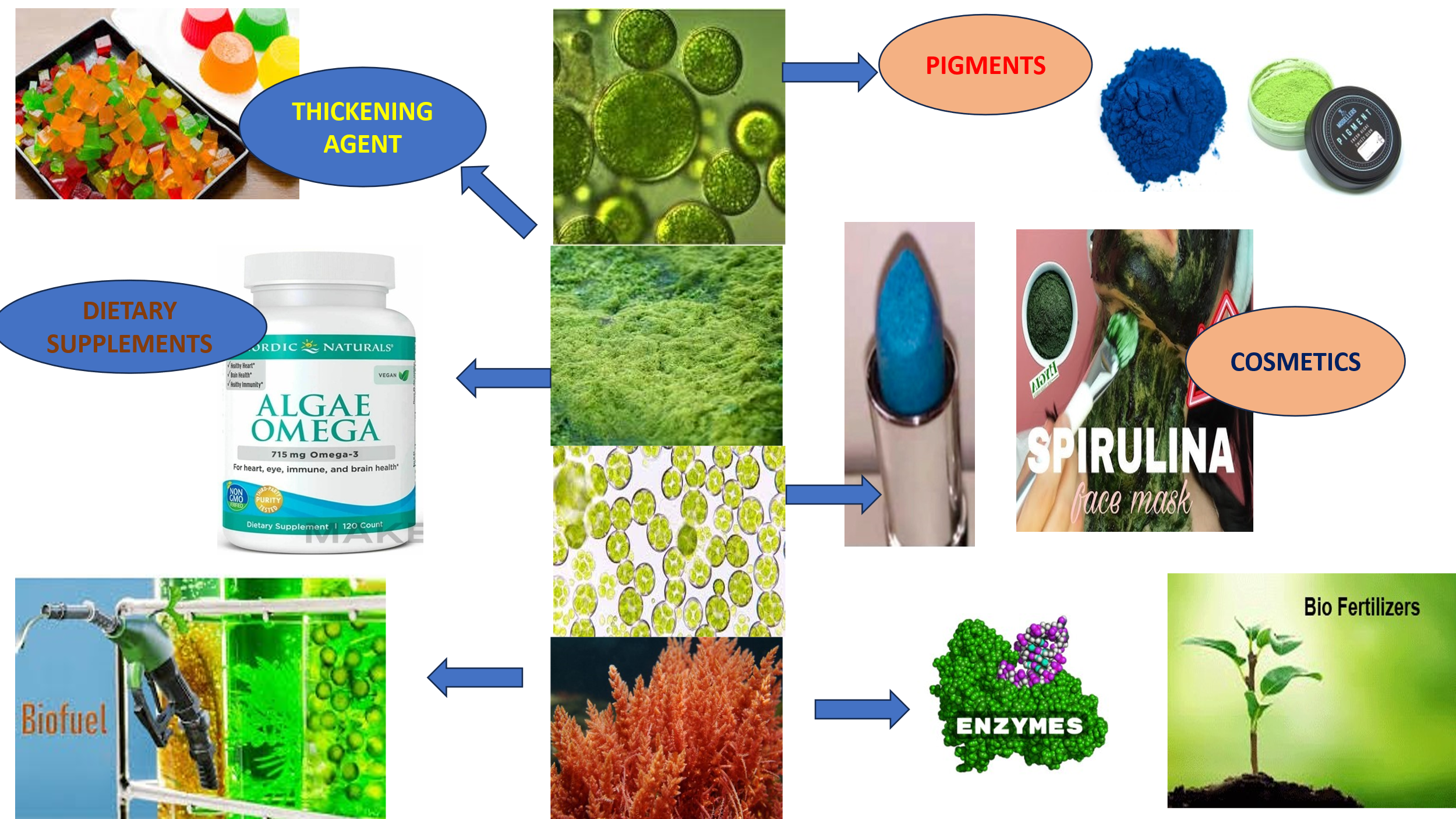
1. **Introduction**

Former few decades have witnessed a continuous hike in demand for food, energy, and materials (Agarwal et al. 2020). This is presumed to grow day by day. According to Worldometer data, the global population was 8.1 billion people in 2024, and it is assumed to rise to 10 billion by 2057 (Worldometer 2024). The efficient usage of natural resources would only be able to suffice the hike in requirement for food, materials, and energy. The food demand is presumed to rise from 59 to 98% by the year 2050 (Ahmad et al. 2022). The present use of crude petroleum as the principal resource of energy and materials cannot be continued for a long time as it is non-renewable and is responsible for increased emission of greenhouse gases and climatic changes (Amini et al. 2020). Exploration of sustainable, renewable and an alternative if crude petroleum is timely required. Agricultural crops and their products, lignocellulosic feedstocks (energy crops, agro-residues, forestry wastes, and grasses etc.), and algal biomass are amongst the assuring substitutes of petrol or crude petroleum that have exhibited outstanding growth and could be promising environment friendly base products (Chen et al. 2021). Biorefinery facility assembles the biomass conversion, technical configurations, equipment/machinery and facilitates to generate power, fuels and chemicals from a diversity of biomass (Bhatia et al. 2024a). Indeed, the perception of biorefinery can be counted equivalent to conventional petroleum refineries. Biorefinery can be categorised into two types: conventional biorefinery and advanced / modern biorefineries. Conventional biorefinery deals with the production of wine, beer, vegetable oil, and paper and is in existence from centuries (Bhatia et al. 2024b). The present century has witnessed the production of wheat and corn, starch-based products as a consequence of revolutions in food production (sugar, potato starch) in the mid-19th century (Sarangi et al. 2022). Modern biorefineries aims towards the exploration and valorization of lignocellulosic feedstocks, algal biomass into fuels, energy, value-added chemicals and nutraceuticals. Modern biorefineries are under expansion stage and have the prospective to satisfy to the escalating need for energy, food/feed, and house-hold products in a coming time (Srivastava et al. 2021). Usually, algae have been investigated for producing vitamins, amino acids, feed and other commercial products at an industrial scale. Algae are inherently rich in carbohydrates and oils and hence have being taken into consideration as a convincing source of biofuels and renewable platform chemicals. Algae are potential candidates in third-generation biorefineries as they can transform CO2 into renewable fuels and biochemical (Bhatia et al. 2020). First (1G) biorefinery uses crop grains or juice, second (2G) biorefinery uses lignocellulosic residues and third-generation (3G) biorefineries employs algae biomass for producing high-value products like vitamins, amino acids, biopigments, and antioxidants (Shubha and Kifle 2018). Integrations of these biorefineries is essential to acquire aforementioned high-value products in unification with commodity chemicals and bioelectricity. The repercussion of 3G biorefinery for producing biorenewables will allow complete expansion of a circular economy (Dominković et al. 2018).

1. **Principle feedstock for 3G biorefinery**

Broad range of microalgae are able to fix greenhouse gases like CO2 and are able to convert them into oxygen through photosynthesis. These organisms are either unicellular or multicellular and most of them are able to thrive in harsh environmental stress factors (Bhatia et al. 2023a). Algae are able to obtain their nutrition from nutrient poor water and can generate enormous quantity of biomass. Industrial wastewater can be employed as a cheap feedstock for the producing high value-added sustainable products by algae (Mehariya et al. 2021a). A statistical survey depicts that 1 kg of algal biomass can be generated in approximately 333 L of water, whereas production of agriculture crop, i.e., 1 kg of soybean needs 2204 L of water (Bhatia et al. 2023b). Mostly, microalgae are aquatic unicellular biomass comprised of basic organic and inorganic elements. Algae varies in their composition of various amounts of protein, carbohydrates, and lipids. Solar energy is used by algae to generate their biomass along with the accessibility of nitrogen, phosphorus and carbon dioxide. This method is much more effective and fast than the plants on land. Micro algae is able to sustain in diverse spectrum of extreme environmental conditions (Mat et al. 2020). Micro algae can be harvested in an economic and an eco-friendly way as it is able to recycles varied range of waste materials. Micro algae differ from lignocellulosic waste in terms of its system elements that are proteins, lipids and carbohydrates, whereas lignocellulosic waste it is cellulose, hemicellulose, and lignin (Bhatia et al. 2023c).

Algae function as a base feedstock for 3G biorefineries as potential raw material for bio-renewables production. Wide-range of market investigation exhibits that diverse ranges of microalgae are most potential industrial biocatalysts (Garcia et al. 2021). Broad ranges of micro algae species exist in nature comprising *Chlorella vulgaris, Haematococcus pluvialis, Dunaliella species*, *Nostoc* spp*.,* *Arthrospira (Spirulina)* have been utilized for valuable products generations. *Arthrospira (Spirulina)* and *Chlorella sp.* are one of the most usable microalgal communities in food and bio-nutraceuticals industries (Gifuni et al. 2019). Even there are several micro algae, i.e., *I. galbana, N.* *opsisoculata, C. muelleri, C. gracilis, P. Tricornutum* which are potential cell factories to generate therapeutic biomolecules concerning antioxidant, anti-inflammatory, antitumor, and anticancer, antiaging, anti-tanning attributes. Microalgae are the significant source of bio-colorants, amino acids and many structural carbohydrates that are regarded as high-value nutrients (Goswami et al. 2022a). Production of microalgae is escalated at industrial level upon its use as a nutritional supplements for human consumption. Nutraceutical and food sector are profoundly using the biopigmented molecules formed by microalgae. Microalgae (Chlorella sp., Dunaliella sp., Scenedesmus sp., etc.) and cyanobacteria (Nostoc sp. and Spirulina sp.) are contemplated as significant resources of health supplements and fine chemicals (Goswami et al. 2022b). For example, Haematococcus pluvialis is a convincing natural source of astaxanthin, a keto-carotenoid. Astaxanthin are known for their antioxidant properties that makes it an ideal supplement of the human diet. Applications of microalgal biomass as value-added products is relevant in nutritious food/feed, cosmetics, and pharmaceuticals industries (figure 1). Third-generation biofuels procured from algal biomass appears to be potential replacements for respective ancestors (Su et al. 2015). Algal regimes have several benefits over lignocellulosic biomass, like as higher lipid accumulation rate, higher light conversion efficiency, extraordinary growth rates, making them a viable resource for the commercialization of bioenergy sectors. Furthermore, a sustainable process and carbon emission way of biofuel generation is feasible(Ubando et al. 2019). Figure 1 depicts the products of third generation biorefineries.



**Figure 1 - Products of third generation biorefineries**

**3. Sustainable Utilization of Micro-Algal Biomass Towards Sustainability**

**3.1. Microalgae As Potential Bioenergy Producers**

Quality of living is an outcome of universal economic growth that is sustained by energy resources. Energy resources are one of the most inevitable indispensable requirements.

Consumption of fossil fuels is increasing rapidly as the global population is rising. This leads to the rapid depletion fossil fuel reserves consistently (Ding and Grundmann 2022). Generation of bioenergy from algal biomass serves a novel platform and a sustainable approach towards the aforementioned global problem. Use of algae as an energy reservoir is an alternate approach that not only reduces the dependency on fossil fuels, but also helps in maintaining the ecological balance, food safety and securing regular energy domain, etc (Chung et al. 2022). Microalgae has became a most potential future platform due to various commercial application, leading towards the synthesis of value added biomolecule along with the bioremediation of waste biomass (Khan et al. 2018).

**3.1.1. Biofuels**

Biofuels are the source of energy which occur as solid, gaseous and liquid forms. Biofuels have been acquired from broad varieties of inexpensive raw materials like soybean, corn, rapseed, sunflower, palm without affecting the food chain. Numerous bioprocess engineering methods helps in generating biofuels from micro algae biomass (Jeswani et al. 2020). Various properties of micro algae like high natural oil production capability, economic sustainability, higher efficacy to accumulate triaceyl glycerol (TAG), higher biomass yield, nontoxicity, CO2 fixation efficacies make them capable for the production of biofuels. *Thalassiosira pseudonana, Nitzschia frustulumm, Skeletonema* *costatum, Micromonas pusilla, Microcystis aeruginosa, Cyclotella cryptica, Chaetoceros gracilis,* *Aphanothece microscopica Nageli, Porphyridium cruentum* microalgal species are the potential producers of syngas and biohydrogen via gasification process. *Nannochloropsis* sp*., Nostoc* sp., *D. salina, G. partita,* and *Cosmarium* sp*,* can potentially generate acetone, ethanol, butanol via the fermentation process. Some microalgal species *T. suecia*, *B. braunii, C. vulgaris, C.* *cohnii, Cylindrotheca* sp.*, Nitzschia* sp.*, Schizochytrium* sp.*, P. Tricornutum* are rich source ofbiooils per unit dry weight (i.e., 15–75%) that can potentially generate bioenergy (Gajda et al. 2015). *Scenedesmus obliquus* contains 40–55% lipid per dry weight biomass that makes it potential producer of biofuels generations employing inexpensive feedstocks (Cardona Alzate et al 2023). Microalgal biomass can show higher productivities of aforementioned biomolecules which ranges from About 1000–4000 gallon/acre/yr of aforementioned biomolecules are produced by microalgal biomass in comparison to the utilization of any other cheaper raw feedstock (Gabrielle and Gagnaire2008).

**3.1.2. Biodiesel**

Presently microalgae are potential biocatalysts that are used for producing biodiesel by employing broad range of waste materials under different environmental accessibility zone. Production of biodiesel from algae has no competition with food chain and this process of producing biodiesel is better than chemical approaches (Khoo et al. 2020). Few microalgae like *C. vulgaris, C. protothecoides* have high amount of microbial fatty acid-based oils, and hence are able to produce high biodiesel yield. About 16 to 68% of oil have been produced by microalgal biomass. *Chlorella sorokiniana* is considered as predominant biocatalyst as it is capable of producing good quality of algal diesel. *S. obliquus* contains comparatively high amount of saturated (56.4%) and unsaturated (43.6%) esters and linoleate (11.42%) (Xu et al. 2022). The saturated esters are potential producers of biodiesel. *Scenesdmus* sp. is one of the most popular and potential biocatalytic producer of biodiesel amongst microbial communities. Few scientific studies of these species revels that their surface level contains lipid layer, alcoholic groups, carboxyl groups which are efficient for producing biodiesel (Khanum et al. 2020).

**3.1.3. Biohydrogen**

Heat content of biohydrogen is highest (143 GJ.ton–1) in comparison to any other fuels presently available. It is a unique fuel as it is not connected with any carbon atom (Giwa et al. 2023). Biohydrogen production is a biologically mediated acidogenesis processes where organic compounds are transformed into high value-added bio products like hydrogen, volatile fatty acids and pyruvate (Bhatia et al. 2021). *Chlamydomonas reinhardtii, Platymonas subcordiformis, S. obliquus*, *Chlorella sorokiniana,* *Chlorella fusca,* *Chlorococcum littorale, Dunaliella* sp*,* *Micromonas* sp*, Parachlorella kessleri,* and *Scenedesmus*, etc.are the prominent producers of biohydrogen. *Ulva lactuca* generates high amount of hydrogen after hydrothermal pre-treatment ~0.14 gm.gm–1 biomass yield (Goswami et al. 2021a).

**3.1.4. Biomethane**

Microalgae are a prospective regime of microorganisms that can catalyse the generation of biomethane. In global market it has received attention due to its significant productivity of valuable by-products likes biomethane that is also known as biogas (Rodriguez et al. 2018). Biogas is chiefly comprised of biomethane (~55–75%) and CO2 (~25–45%) in anaerobic conditions. Biomethane is being utilized as biogas and can be further transformed into bioelectricity. Microalgal species like *Ulva* sp*.* generates volatile solid based 180 mL/g methane in mesophilic condition (35℃) during anaerobic digestion. *Laminaria sp.* produces 0.26–0.28 m3 kg–1 of biomethane (Eggemann et al. 2020). Yield of biomethane is comparatively higher contemplating micro algal biomass rather than lignocellulosic biomass like grass, wood, etc. Furthermore, presently mixed microbial consortia methods have been introduced to cultivate two or more species of micro algae for generation of biomethane employing waste water treatment plant effluents. This method is not only cost effective but is also industrially viable and sustainable (Shrivastav et al. 2021).

**3.1.5. Bioethanol**

Microalgae are the efficient producers of bioethanol as a virtue of their distinguished physiological features like higher photosynthetic capacity, higher amount of biomass productivity, higher carbon dioxide sequestration, thin cellulosic cellular wall, wide spectrum of metabolic diversity and variable chemical cellular constituents (Goswami et al. 2021b). Algae like *Chlorococcum, Chlorella, Chlamydomonas, Scenedesmus, Tetraselmis* species are rich in carbohydrates and hence are potential producers of bioethanol. *Chlorococcum sp.* and *Chlorella vulgaris* have significantly applied to produce bioethanol. *Chlorococcum infusionum* microalgae produces significant amount of ethanol by the alkaline hydrolysis process. It contains 26.1% (g ethanol/g algae) (Goswami et al. 2021c).

**3.1.6. Biobutanol**

Biobutanol is a biofuel that has been applied as potential transportation fuel for over a decade. It has lower vapor pressure and higher energy density. Economic production rates of biobutanol are parallel to that of ethanol. Biobutanol is considered the better alternative to ethanol, petroleum as biofuel additives. Bacteria utilizes the cellulose content of algal biomass, during the production process of butanol (Khan et al. 2018). Bacteria also digest starch and reduces the residual sugars during this process. Microalgae *Ulva lactuca* produces biobutanol in company with *Clotridium species.* Brown algae *Saccharina* sp. ferments biobutanol after acid treatment of organic matters. Biobutanol production yield lies on the range of 0.12 g g–1 to ~0.16 gm.gm–1 which is lower in comparison to ethanol molar yield (Paul et al. 2014).

**3.2. Algae-Based High Esteem Appended Commodities**

Algae are the reservoir of new value-added molecules and products round the world. Diversity of microalgal regimes that can generate high esteem appended molecules is huge. Different value-added products like pigments, proteins, vitamins, excessive amount of PUFA (Poly unsaturated fatty acid), etc can be gained out of 30,000 known species (Prabha et al. 2022). Microalgae are capable of producing diverse forms of secondary metabolites as they are capable of thriving in diverse environmental conditions. This characteristic is unique to algae. *Dunaliella species, Chlorella species* and *Spirulina species are* the three types of microalgae *that are the known producers of* high value-added components. *Arthrospira platensis* species produces Phycobiliproteins (a high value-added molecule) that has many applications in various therapeutics nutraceutical(Kumar et al. 2020).

**3.2.1. Pigments**

Pigments are colourful chemical constituents that absorbs light energy and participate in photosynthesis and ATP generation. Pigment absorbs certain wavelengths of visible light (Bijon et al. 2022). Pigments obtained from microalgae are known for their health promoting properties, excessive availability, and their high market value. There are three chef pigments found in microalgal species. They are carotenoids (provide orange, yellow color), phycobilin (red or blue natural colorant), and chlorophyll (green colorant) (Solarte-Toro et al. 2021). *Chlorella vulgaris* is one of the potent microalgal species which provides various forms of pigments in diverse culture condition (Table 1).

**Table 1 – Production of various pigments by Algae** (Solarte-Toro et al. 2021)

|  |  |
| --- | --- |
| Pigments | Production (μg.gm–1 dw) |
| β-Carotene | 7–12,000 |
| Astaxanthin | 550,000 |
| Violoxanthin | 10–37 |
| Pheophytin-a | 2310–5640 |
| Chlorophyll-β | 72–5770 |
| Chlorophyll-α | 250–9630 |
| Lutein | 52–3830 |
| Cantaxanthin | 362,000 |

dw = dry weight

*Dunaliella bardawil* are rich in β-carotene. β-carotene inhibits the oxidation of lower density lipoproteins (LDLs) and enhances the levels of plasma triglycerides, cholesterols and high-density lipoproteins (HDLs) in mouse and humans (Markou and Nerantzis 2013). Highest amount of astaxanthin is procured from *Chlorococcum, Scenedesmus, Chlorella zofingiensis. Dunaliella* *tertiolecta*, *Chlorella ellipsodea*, and *B. braunii* are the known producers of pigment Violaxanthin (Ncube et al. 2022). Violaxanthin has anti-inflammatory properties and strong antiproliferation properties against human mammary cancer cells. *Nannochloropsis sp.* especially *N. salina, N. oculata,* and *N. gladitana*, etc are the chief producers of pigment Canthaxanthin that is employed in food additives. When employed as a feed for poultry, Canthaxanthin imparts skin and egg yolk coloration. It is also utilized in aquaculture salmonid, and sausage colorants (Espada et al. 2020).

**3.2.2. Cosmetics**

Bioactive compounds are found in microalgae that are involved for ameliorating treatment of skin related functions. Pigments found in algae are employed as colorant for various cosmetics (Bhalamurugan et al. 2018). Microalgae are used as antioxidant agents and water absorbing biomolecules. *C.* *crispus, M. stellatus, A. nodosum, A. esculenta, S. platensis, N. oculata, C. vulgaris and D. salina,* *Euglena gracilis are* some classical microalgal sp. that are potentially applied in cosmetics industries (Nilsson et al. 2022). It is applied for skin and hair care value added biomolecules. *Spirulina* Whitening Facial Mask, *Spirulina* firming algae mask, *Spirulina* Facial Scrub, etc. are some examples of cosmetics products that are comprised of herbal extracts andproteins (Sathasivam and Ki 2018). These products improve the immunity of skin’s, balance the skin moisture, removes the deadly skin surfacetissue cells from skins as cleaning agent and vitalize the tissues associated with skin surfaces (Ubando et al. 2022). Microalgae has the potential to protects the skin and hair from harmful radiations of ultra-violet light. Recently microalgae have gathered huge attention as it is able to resolve various skin ailments like aging, tanning, antioxidant, etc. Natural pigments are able to protect against, skin cancer, cutaneous inflammation and melanoma disorders (Geissler and Maravelias 2021).

**3.3. Microalgal-Derived Compounds for Human Usage**

**3.3.1. Bio-Fertilizer**

Microalgae are employed as biofertilizer as an inconsistent component for many decades. It is used as a substitute of chemical fertilizer, it is cheap and is comprised of natural compounds, hence in many cases it is a naive component than chemical fertilizer. When microalgae is used as a biofertilizer it offers several benefits like plant growth, seed germination, soil conditioner in various agricultural yields (Vance et al. 2022). This is because it is rich in nutrients. Biofertilizers plays a vital role in growth of plants and it enhances the fertility of soil. Algae like *Cylindrospermum* sp*., T. tenuis, Nostoc muscorum, Hapalosiphon fontinalis* are a rich source of vitamin-B12. Indole-3-acetic acidindole-3-propionic acid or 3-methyl indole are prevalant in *Nostoc, Hapalosiphon sp*. These compounds helps in the promotion of growth in plants, binds soil agent and aids in soil aggregation. Microalgae *Haematoccus pluvialis, Nannochloropsis salina* are known to produce nitrogen-based bio-fertilizer (Mobarezkhoo et al. 2022). *Chlorella KR-1* strain has shown higher efficiency of carbon-di-oxide fixation up to ranges from 10–50% CO2 (v/v). *Spirulina sp.* exhibits inversely proportional carbon-di-oxide concentration during the growth rate, biofixation rate (Cheah et al. 2014). *S. incrassatulus* and *S. dimorphus* exhibits elevating proportion of carbon sequestration in comparison to other microalgal species. Table 2 depicts some potential microalgal species and their carbon fixation rates.

**Table 2- Potential microalgal species and their carbon fixation rates (Patel et al. 2016).**

|  |  |
| --- | --- |
| Microalgal species | Carbon fixation rates (g.L–1.d–1) |
| *Scenedesmus incrassatulu* | 1.50 |
| *Haematococcus pluvialis* | ~0.14 |
| *Chlorella kessleri* | ~0.16 |
| *Chlorella vulgaris* | 0.25 |
| *Dunaliella tertiolecta* | 0.27 |
| *Dunaliella* sp*.* | 0.31 |
| *C. vulgaris* | 0.43 |
| *Scenedesmus dimorphu* | 1.27 |
| *Spirulina platensis* | 0.92 |
| *Chlorella* sp. | 0.7 |
| *Scenedesmus sp*. | 0.61 |
| *Scenedesmus obliquus* | 0.55 |

**3.3.2. Biofibers in Paper Industries**

Algal polysaccharides present in wide range of algal species are rich in sulphur and provide massive structural constancy. Sometimes. paper production employs microalgal species that are rich in cellulose as a potential feedstock. Few studies have shown that algal mixture isolated from wastewater plant was mixed with ten percent pulp, enhanced the texture of paper without decreasing brightness. This was an economic and a cost-effective approach for paper production as 45 percent lower material cost was involved in this process (Sharma and Sharma, 2017).

**3.4. Microalgae As Food and Dietary Supplements**

The concept of “Functional Food” was first developed in 1980s in Japanese continent. As some microalgae are rich source of omega 3 fatty acids, vitamins and amino acids, they are taken as food supplements to fulfil the gap of various nutrients of main food. Same concept applies for their use as animal feed additives (Sathasivam et al. 2019). *Spirulina* sp. is rich source of essential protein, γ linolenic acid, vitamin and mineral. It is one of the emergent microalgal regimes, the dietary supplements of which are globally produced (3000 t/year). Consumption of microalgae bestows many health benefits as it protect health against arthritis, diabetes, cardiovascular diseases, hypertension, anemia and cancer like many diseases (Barkia et al. 2019). Phycocyanin and vitamin E are the antioxidant compounds, that are prevalent in *Spirulina*. Omega 3 fatty acids are found in *Isochrysis galbana* which are used for making biscuits as a processed food. Food and DrugAdministration, USA has given *Chlorella* sp. the status of GRAS i.e., generally recognized as safe as there are several applications of this organism (Camacho et al. 2019). It is used as a noodles, tablets, powders,nectar, fruits and vegetable preservative. Taiwan and Klotze, Germany are the known producers of *Chlorella* basedproducts. Their production reaches 2000 tons annually (Molino et al. 2018). *Chlorella vulgaris* has been used as a supplement as fish foods. Consumption of *Chlorella* basedproducts increase immunity, shows hypoglycemic effects, prevent tumor and cancer cells, lowers the bloodpressure etc. Hence it is appropriate to say that Chlorella based food show various intact roles in health sectors and cures many diseases (Mehariya et al. 2021b).

**3.4.1. Microalgae As Potential Aquaculture Feed**

Microalgae are comprised of significant amount of proteins, amino acid, lipid, vitamins, carotenoid, and energy that makes them appropriate for use in aquafeed industry as a high quality aquaculture feed. Few researches revels that in late exponential growth phase, generally microalgae have been enriched with ~30–40 % (w/w) protein, ~10–20 % (w/w) lipids and ~5–15 % (w/w) carbohydrates (Shah et al. 2018). Canthaxanthin and astaxanthin are the carotenoid that are prevalent in *Haematococcus pluvialis sp*. These carotenoids acts as coloring agent of salmonids flesh. In last few decades over hundreds of microalgal systems have been used for aquafeed but still less than twenty species have reached importance in aquaculture industry. The plus point associated with the usage of microalgae as animal feed is that they are rich in nutritional value, has easy availability, are less toxic, and easily digested (Sirakov et al. 2015).

**3.4.2. Microalgae As Jellifying and Thickening Agents**

Alginate is derived from brown algal species such as *Macrocystis* sp.*, Lessonia* sp., *Laminaria* sp.*,* *Durvillaea* sp and *A. nodosum*. Alginate is comprised of α L guluronate and β D-mannuronate.Alginate is used as a gelling and chelating agent. It finds its utility in textile industry for sizing cotton yarn. It finds its application in food and pharmaceutical sector because of its chelating properties, for making highly viscous solutions. Alginate has also moisture retention properties, that makes it suitable for many food industries (Khanra et al. 2018).

Agar is the mixture of polysaccharides compounds that are obtained from the genera of red algae (Rhodophyta) like *Gracilaria and Gelidium.* Agar is used as a food additives in sweet dishes, candy chocolates, fruit juice, jam etc. It also has an industrial application like in sizing of papers, printing in textiles, in molecular biology etc.In 2019, 12,000 tons/year agar has been generated from various algal species (Sharma and Sharma 2017).

Carrageenan is another potential product of algae and has a huge impact in health management. It is a natural polysaccharide. USA is a global leader in production of Carrageenan. It is obtained from rhodophyta. Important genera of rhodophyta producing Carrageenan are *Gigartina* sp*., Chrondrus* sp*.* and *Euchema* sp. Carrageenans are water soluble compounds and it finds its application for food applications like dairy, meet, desserts, etc. It is used as emulsifying and stabilizing agents in several food industries (e.g., jellies, jams, deserts, meat products). In addition, carrageenans act as anticoagulant, antitumor, antiviral, agents (Drexler and Yeh 2014).

**3.5. Enzymes derived from Algae**

Currently, the downstream processing of commercially available bacteria and fungi-based enzymes is very expensive and is responsible for increase in overall cost of production. Algae are an excellent source of various enzymes of industrial importance. Past few decades have observed the advancement in algal genomics, because of which the algal machinery could be employed for enzyme production by genetic modification. This approach will be cost effective for the generation of various enzymes and other value-added products. Presently, the advancement in biorefinery approaches minimizes the cost of production of algal enzymes and intensify the economic sustainability of the process (Khan et al. 2018). Table 3 depicts few examples of enzymes produced by algae and their applications.

**Table 3 – Commercial enzymes obtained from algal regime, their characteristics and applications**(Raposo et al. 2013, Liu et al. 2017, Brasila et al. 2017).

|  |  |  |  |
| --- | --- | --- | --- |
| **Enzymes** | **Characteristic** | **Produced by Algae** | **Applications** |
| Carbonic anhydrase | Metalloenzyme with Zn2+ at the active site | *Acutodesmus sp., Kirchneriella* sp. and *Desmodesmus sp.* | Metabolic processes such as acid–base regulation, biomedical applications (artificial lungs, biosensors and CO2 sequestration systems, drugs), biofuel production and transportation of carbon dioxide and bicarbonate. |
| Cellulases | Disintegrate the polysaccharides units of cellulose to simpler forms i.e., β-glucose | *Chlamydomonas sp., Scenedesmus sp., Dunaliella sp.* | Bioenergy sector, food industries, textile industries, detergent industries and agricultural sectors. |
| Amylase | Hydrolyses starch, oligosaccharides and polysaccharides | *Rhizoclonium* sp, *Spirogyra* sp, *Klebsormidium* sp, *Rhizoclonium hieroglyphicum* and *Oedogonium* sp | Detergent industries, Food industries |
| Protease (endo and exo peptidases) | Hydrolyse amide linkages in protein biomolecules | *Chlorella vulgaris* and *Anabaena variabilis* | Food, chemicals and pharmaceutical industries |
| Lipase | Triacylglycerol acylhydrolases (EC 3.1.1.3) responsible for the hydrolysis of triacylglycerols having long chains | *Botryococcus sudeticus, Isochrysis galbana* and *Chlamydomonas reinharditii.* | Food, detergents, pharmaceuticals, and bioremediation |
| GOX (β-D-glucose: oxygen oxidoreductase, EC 1.1.3.4) | Inhibit the function of α- glucosidase. | Brown algae *Ascophyllum nodosum* | Industrial aspects in therapeutics specially to manage type II diabetes |
| Tannase | also known as tannin acylhydrolase (EC 3.1.1.20).) It catalyzes the hydrolysis of ester bonds presents in gallotannins, complex tannins and gallic acid esters | *Cyanobacterium phormidium valderianum* BDU 140441 | Food, feed, chemical and pharmaceutical industries. |

1. **Conclusion**

Looking on to the global uncertainties presently prevailing in terms of climate change, political instabilities and requirement for food/feed in future, it is high time improve the scalable technologies of 3G-biorefineries for the commercial production of fuels, food, and renewable chemical commodities. This would curtail the dependence over the petroleum products and participate in the formation of a sustainable society. Among several biorefineries, algal biorefinery holds an outstanding position as a future technology. Algae is a significant source of various biofuels, enzymes, food additives, biofertilizers, dietary supplements and many more. Advancement of 3G-based algal biorefineries would provide sustainable products and would make the production process cost effective or economically feasible. The combination of biorefineries could provide chemicals and fuels at reasonable cost rather than individual facilities. Third generation alga-based biorefinery has a huge scope in a coming time, as it provides the continuous supply of various algal products in a sustainable manner. Biorefinery remains to collect an impulse towards encompassing the research inclinations towards sustainable bio-based products.

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Details of the AI usage are given below:

1.

2.

3.

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