

Algae as a Sustainable Resource: Cultivation Methods and Applications: A Review

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Abstract- Algae are most diverse group of photosynthetic organisms on the planet, with an estimated different species present in the Earth 's water bodies and terrestrial environment. Since, high rate of biomass accumulation and low resource input requirements when compared to traditional terrestrial crops, driven largely by consumer demand for live food, feed, pharmaceutical, agricultural and environmental applications. Algae cultivation, which include open-system, closed-system and hybrid photobioreactors, and the range of practical downstream harvesting procedures, before summarizing a wide range of commercial applications such as solid and liquid Biofertilizers, Degradation and biosorption of coloured synthetic dyes from textile effluents, phytoremediation of organic waste streams, and base-market applications such as algae-derived yarns, biodegradable papers and natural colorants. as well as the role they play in carbon dioxide sequestration, nitrogen and phosphorus removal in wastewaters and the various pathways toward a circular bioeconomy. These reviews Include the needs for future research in the field of algae cultivation and utilization. Algae have great potential for solving many of the world 's technological, food security, environmental pollution, energy and climate change related problems.

Keywords: *Algae, Biomass, Cultivation, Biofertilizers, Degradation, Phytoremediation, Biodegradable*

I. INTRODUCTION

Algae are a group of organisms that have the remarkable ability to make food from the sun. Their origins trace back to the beginning of life on our planet, over a billion years ago. Algae include photosynthetic organisms that range from the unicellular microalgae that are invisible to the naked eye, such as Chlorella, Spirulina and Chlamydomonas, to the giant multicellular macroalgae, commonly known as seaweeds. Algae contribute about fifty percent of the Earth 's oxygen by consuming carbon dioxide, and are at the base of many food webs within aquatic habitats. Recently there has been significant interest and research

interest due to their great productivity biomass, biochemistry and diverse environments. Algae With a worldwide increasing request for new renewable resource, people become more and more interested in using algae as an alternative biological system. As they can produce fast biomass and fixate carbon efficiently, algae provide an interesting way to fight climate change. Phycology studies have shown that microalgae can fix CO₂ at a rate much higher than terrestrial plants (Chisti, 2007).

Algae may be cultured in areas that do not offer land, require saline or waste water as a source of nutrients, and may be used to remediate nutrient-rich wastewaters, preventing them from entering streams and reservoirs (Rawat et al., 2011). Algae uptake of nutrients makes them ideal candidates for nutrient removal, especially for nutrients such as nitrogen and phosphorus which can lead to eutrophication (Craggs et al., 2012). The global algae market has grown continuously over time due to market demand for its use in food, pharmaceutical, biofuel and agricultural application. New reports suggest the market for algae-based products is expanding due to the increased awareness of environmentally-friendly products and circular bioeconomy models (Kumar et al., 2022).

Further interesting property of the algae is that they can absorb the heavy metals and broken down, absorb the toxic organic pollutants e.g. dyestuffs from the textile industries (Abdel-Raouf et al., 2012). The fact that it not only produces biomass but also cleans up the environment makes algae ideal for sustainable wastewater treatment schemes. Besides present ecological usefulness, the enormous economic value of the use of algae should also not be ignored due to their wide applications. Because algae contain high amount of proteins, carbohydrates, vitamins, Lipids, pigments, and secondary

metabolites. they are used in many fields. For instance, the food supplements *Chlorella vulgaris* and *Spirulina platensis* are being commercially used so far because of their nutritional content (Becker, 2007). Actually, algae have been applied on production of biofertilizer, bio fuel, biodegradable materials, natural pigments and many other products. Phycocyanin, chlorophyll, carotenoid and other algal pigments are described as some of the high-value natural colorants used in food, cosmetics and biomedicine (Guedes et al., 2011). Such potential benefits make macroalgal feedstocks so attractive that need further research. However, problems such as cost-efficiency of production, the use of energy consuming methods for harvesting and instability of cultures are limiting the mass cultivation of macroalgae. New technologies of cultivation, genetic modification and biorefinery methods are however addressing these issues (Khan et al., 2018; Patel et al., 2021).

Overall, algae as a innovator in diverse chemicals and biomaterials exploration are a potential, reliable terminal for the world energy, environment and food problems. In addition, the potential application of algae are extensive, not only for bioremediation but also other than for use as a raw for alternative biomass production of textiles, papers, colorants. With respect to textiles, researchers have found that the novel algal fibers have appealing alternatives as the fiber properties presented is similar to cellulose fibers. In addition, the biodegradability of seaweed alginates has been discussed and it's proven that it might has the potential to replace the traditional petroleum-based plastics as a raw material. As for papers, it has been tested and suitable to make paper products with algae biomass rather than wood pulp. The microalga such as spirulina as an natural colorants has been proven to be applicable in food, cosmetics, textiles, and inks.

II. ALGAE: CLASSIFICATION AND GENERAL CHARACTERISTICS

The classification of algae is based on pigmentation, cell structure studies into major groups such as Cyanophyta (blue-green algae/cyanobacteria), Chlorophyta (green algae), Phaeophyta (brown algae), Rhodophyta (red algae), Bacillariophyta

(diatoms) and Chrysophyta (golden algae). Algae are generally conventionally divided into Microalgae (normally unicellular or colonial microscopic types) and Macroalgae (more common in multicellular forms occurring in marine systems) (Lee, 2018). some 72,500 species have been associated with taxonomy, though 10 times this number are estimated to exist. High Productivity and Growth Rate of Microalgae show volumetric biomass productivities of 1–5g. L⁻¹. Day⁻¹ in closed photobioreactors, which are significantly higher than that of terrestrial crops such as soybean or sugarcane (Chisti, 2007; Stephens et al., 2010). Their capability of continuous growth in controlled environment allows them to be produced during all year without depending on seasonal changes.

The wide-ranging biochemical composition of algae proteins, lipids, carbohydrates, pigments, vitamins and other bioactive compounds reflects a feedstock portfolio not matched by any other organism. The diversity in biochemical composition means that algae can be used as either food, feed, fertiliser, biofuel feedstock, medicine and raw material for biomaterials in, for example an integrated algal biorefinery (Chew et al., 2017). Algae based production systems are generally shown to produce much lower greenhouse gas emissions than conventional petrochemical counterparts and also compare favourably to life cycle assessments of various microalgal bioproducts reductions vs. a synthetic equivalent (Sills et al, 2013). Aside from greenhouse gas savings, algal cultivation in wastewaters also combines tertiary wastewater treatment, removing reactive N and P in the water and limiting the eutrophication potential of discharges to natural waters bodies (Craggs et al., 2012).

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eutrophication potential of discharges to natural waters bodies (Craggs et al., 2012).

III. CULTIVATION METHODS OF ALGAE

In the recent researches in last years of algae technologies the general element which is verify to be the success key of algae technology is the cultivation. The cultivation techniques are generally classified into three main modes of cultivation were open pond culture, photobioreactors and recently the hybrid technology which is the combination of the two.

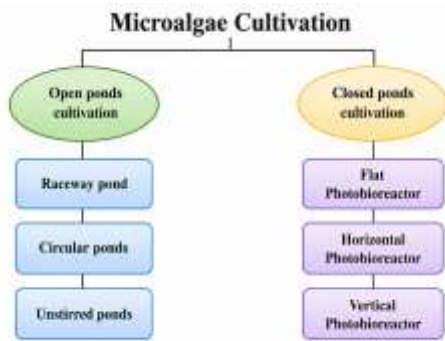


Fig 1. Different Methods of Algae Cultivation
Modified from Ijaola et al. (2023)

3.1 Open Cultivation Systems

Open cultivation systems currently represent the most mature and widely-used method for commercial-scale algae production. These are traditional, natural systems (lakes, lagoons, ponds) and modern, artificial systems (open raceway ponds). In the latter, which is the most prevalent algae cultivation system at an industry-scale, shallow, 20-30 cm-deep, recirculating channels, where the paddling wheel provides homogenization and counters settling (Chisti 2007). Open raceway ponds are most attractive for large-scale processes, due to the low construction and operating costs, simplicity of scale-up, and availability of free solar radiation. Major drawbacks

are ‘cannibalization’ by competitors, grazers and other predators, large water throughput (and associated losses) due to evaporation, uncontrolled temperature, pH and CO₂ concentration, and rather low areal productivities in comparison to closed systems (Brennan & Owende, 2010). The variety of species is limited to those that can thrive under these conditions, e.g. *Spirulina* and *Dunaliella salina*.

3.2 Closed Photobioreactors (PBRs)

Closed PBRs are engineered photobioreactor vessels which prevent the algal culture from interacting with the outside environment. This allows the solution conditions; temperature, pH, dissolved CO₂, and contamination to be better controlled. Different types have been trialled; for example, a tubular PBR is made of transmissive glass or polycarbonate tubes (3–10cm diameter) arranged either in a horizontal, vertical or helical structure to optimize light utilisation on a given land area. And These systems can produce biomass at a rate of 20–40 g/m²/day and are more suited to the production of high value products, such as astaxanthin, beta-carotene or omega-3 fatty acids (Chisti, 2007). However, some micro-algae are capable of heterotrophic growth, using organic carbon sources (glucose, acetate) in the dark. Heterotrophic fermentation is capable of very high biomass concentrations (>100g/l) and productivities in normal bioreactors, thus making this a commercially attractive process for lipids and DHA production. Commercial reactors grow *Chlorella*, *Cryptocodium cohnii* and *Schizochytrium* using heterotrophic cultivation. Mixotrophic growth, using photosynthesis and organic assimilation simultaneously, gives a compromise in productivity as well as a decrease in light requirement (Wan et al., 2011).

3.3 Harvesting Methods

Table 1. Algae production using these different types of harvesting methods (Ali et al., 2021; Tan et al., 2018)

Harvesting method	Recovery	Pros	Cons
Centrifugation	High	High recovery efficiencies It is simple method to use, it is applicable to fine many microalgae.	Expensive More consumption of energy Cells can be damage because of shear forces.
Filtration	Low-high	Possibility of water recycle High recovery efficiencies	Volume is restricted The membrane replacement and pumping costs are some of the most expensive parts of the process. Slow process
Flotation	High	Suitable for use on a commercial scale Low-cost Space required are minimal	Flocculants chemicals are required Water recycling and product extraction probably could be impacted
Gravity sedimentation	Low	Simple and Inexpensive Recycling of water has the scope.	Slow process Quality loss in microalgal products

IV. ALGAE-BASED BIOFERTILIZERS: SOLID AND LIQUID FORMULATIONS

The use of algae as bio-fertilizer have increased interest since it is more environmentally friendly than the use of chemical fertilizers Biofertilizers based in microalgae and cyanobacteria increase the soil fertility improving plant growth as well as the environmental sustainability. Indeed, chemical fertilizers lead to a leaching of nutrients and a degradation of soils whereas algal biofertilizers lead to an increase of the soil organic matter content and to a boost of the microbial activity: Cyanobacteria like Anabeana, Nostoc and Aulosira are especially important, since they can fix nitrogen from the atmosphere utilizing specific heterocysts where nitrogen is converted into ammonia which is then accessible for plants. This is particularly valuable in fertilizer-depleted soils and has been implemented extensively in rice-based cropping systems (Singh et al., 2016). Microalgae such as *Chlorella vulgaris* and *Spirulina platensis* are a Source of vital nutrients, bioactive substances, and plant growth regulators with proven potential to increase crop yields (Renuka et al., 2018).

4.1 Solid Algae Biofertilizers

Solid algae biofertilizer is usually prepared from drying algal biomass and used directly in soil. They can be used as slow-acting source of nutrients and can be used for long term improvement. When such biomass decomposes, it provides nitrogen, phosphorus, potassium and micro nutrients to soil. Besides nutrient addition solid algal biofertilizer can provide another benefit-improving physical property of soils. Solid biofertilizers considerably increase amounts of organic materials and into soils and as consequence improve structure and aeration of soils, acidity neutralization as well as their ability for retaining waters and penetrability. By addition of algae biomass organic compounds stimulate the growth of rhizosphere microorganisms that has beneficial effects on nutrient cycling. For example, application of dried biomass of microalgae *Chlorella vulgaris* can be very effective in improving soil properties and crop yield (Renuka et al., 2018). In addition, solid formulations are more convenient in field applications because they are more stable and have a longer shelf life than liquids. However, they also have impacts on growth more slowly because release of nutrients depends on microbes' decomposition in the soil.

4.2 Liquid Algae Biofertilizers

Liquid algal biofertilizers are produced from algal extract or suspension and used as spray or drench. These biofertilizers can exert growth-promoting effects quickly through direct contact and absorption of mineral nutrients and bioactive bio-compounds. Other liquid extracts of microalgae, such as *Chlorella vulgaris* and *Spirulina platensis*, are loaded with plant growth-promoting compounds such as Auxins, Cytokinins and Gibberellins. These plant hormones control crucial plant life activities such as cell division and, enlargement and differentiation. They promote the growth of plants and improve their quality of life. Along with them, they contain amino acids, vitamins and antioxidants that improve the quality and tolerance level of the plant to stress (Ronga et al., 2019). It has been shown experimentally that applying algae through foliar spray increases seed germination, chlorophyll content, root/shoot growth and yields of crops (Renuka et al., 2018). Liquid biofertilizers are useful for supplying nutrients at vital stages of development.

4.3 Pot Study Efficacy and Comparison

In its current state, the results from comparisons in pot experiments between solid and liquid biofertilizers of algae is diverse. Every trial resulted in inconsistent outcomes between various species of alga used as the biofertilizer, the material used as carrier, contrasting dosages used, varying species of plant, time since application of biofertilizer, the type of soil used and the planting techniques in each trial.

Some authors have even recommended combining the two forms for use in agriculture (Dineshkumar et al.2019) recommended use of solid biofertilizer at the onset of the planting process or before and the use of liquid biofertilizer applied throughout the growing period, which may be at the start of the season or prior to planting to optimize growth.

4.4 Different Algal Species Used as Biofertilizers

Different species of algae have been exploited as biofertilizers with different mechanisms and modes of application. *Chlorella vulgaris*, a microalga, was found to enrich the soil with nutrients which are very useful for the growth of several crops such as tomato, bell pepper, and spinach (Parmar et al., 2023). *Spirulina platensis* is another microalgal species that has shown efficacy in stimulating seed germination and improving the productivity of several crops by producing growth-promoting substances (Singh et al., 2016). Cyanobacteria are well-known nitrogen-fixing microbes that can convert atmospheric nitrogen into ammonia and store it in their specialized cells, which can then be directly used by plants as fertilizer (Ammar, 2022). *Anabaena* species and *Nostoc* spp. have been widely used as nitrogen biofertilizers. Furthermore, *Oscillatoria angustissima* can be effectively employed to enrich the soil, enhancing crop production (Priya et al., 2022).

Table 2. Comparative overview of algal species used as biofertilizers in different crops

Algal Species	Crop	Application Method	Reported Effects	References
<i>Chlorella vulgaris</i>	Wheat	Aqueous extract and culture filtrate used in seed soaking	Better germination, High percentage of chlorophyll content and activity of crude culture filtrate.	((Minaoui et al., 2024)
<i>Spirulina platensis</i>	Common bean (<i>Phaseolus vulgaris</i> L.)	Foliar spray + Soil addition	Higher photosynthesis, higher antioxidative level, lower concentration of heavy metals, higher plant growth and higher plant yield	(Rady et al., 2023)
<i>Nostoc piscinale</i>	Rice	Liquid extract	Higher growth and chlorophyll content comparable to commercial fertilize	(Oco et al., 2024)
<i>Anabaena</i> sp.	Rice	Biomass dried + urea	decrease in methane emissions, Greater plant height and higher yields	(Vaishyaa & Minishe Sinha, 2024)

V. ALGAE-MEDIATED DYE
DEGRADATION OF TEXTILE
INDUSTRIAL EFFLUENT

The textile industry is one of the most water-intensive and polluting industry in the world, with an estimated annual freshwater consumption of 79 billion m³ and an estimated 20% of all industrial water pollution worldwide (World Bank 2019). The discharge of textile wastes is a mixture of synthetic dyes, surfactants, heavy metals, and chemical auxiliaries. There are over 100,000 commercially available dyes and it is estimated that between 10 and 15% of dye used in dyeing is discharged untreated into waterways. The water becomes coloured, toxic and recalcitrant of the effluent.

Discharge of industrial coloured effluent containing large number of synthetic dyes to natural water body causes serious problems as this dye is toxic and it affects the growth of aquatic species due to the colour and reduces the light Penetration in the water. Synthetic dyes mainly used in textiles have been found to be persistent. Algal species efficiency in decolorising textile dyes. The intermediates of artificially synthesized complex dyes in textile industry are responsible for the chemical oxygen demand (COD), total dissolved solids (TDS) and total suspended solids (TSS) and persistent colour (Tahir et al., 2021)

Synthetic textile dyes are organized into certain groups based on their chemical composition. The groups are azo dyes (>50% commercial dyes), anthraquinone dyes, triphenylmethane dyes, and heterocyclic dyes. Azo dyes is a group that consists of one or more azo bonds (-N=N-), these comprises of reactive dyes, direct dyes, and acid dyes. Multiple azo dyes and its metabolic products are mutagens, and carcinogens as well as endocrine disruptors in the range of aquatic life and the contamination of drinking water (Carmen & Daniela, 2012).

VI. BIO-BRICKS FOR ORGANIC WASTE
DEGRADATION

The using bio-bricks; solid substrate structures with living microorganisms or biologically active material as a means of waste management and environmental

remediation is an innovative and emerging application of biotechnology. For algae-based biotechnologies, it has been proposed and proved that a bio-brick structure consisted of algae biofertilizer biomass in a porous structure of organic or inorganic material could be a novel way of facilitating aerobic degradation of organic wastes (including flower wastes, agricultural wastes, food wastes) (Sharma et al., 2021).

VII. ALGAE-BASED YARNS AND TEXTILE
APPLICATIONS

Innovations on Algae Yarn is an on-going research field in sustainable textile science if you look at the development of algae derived yarns. Technologically, only alginate and other polysaccharides from macro algae are utilized and used to produce fibers. Contrary to the early simplified statement, most of the algae are not able to be spun directly into yarns but extraction of biopolymers such as alginate followed by fiber spinning.

However, one of the problems that can be recognized, is the quite weak strength of the fibers of the alginate according to other fibers of synthetics. It was determined through experiments that these single alginate fibers do not have enough tensile strength and robustness to be used in mass textile production. Thus, efforts are being directed toward development of the composite fibers by the addition of other polymers like cotton, cellulose or chitosan to enhance the mechanical properties. For example, the addition of cotton fibers into alginate solution leads to great improvement in tensile strength and structural stability of the manufactured fibers (Azam, F., et al. 2022). Likewise, the latest findings focus on new natural cross-linkers in order to improve the mechanical properties of fibers (Badrudin, I. A., et al. (2024).

VIII. BIODEGRADABLE PAPERS FROM
ALGAL BIOMASS

Worldwide paper production accounts for a total output of about 400 million tonnes per year of which 90% is made from wood pulp, therefore causing substantial environmental impacts on forest and habitat. There has been some research into alternative

sources of non-lignocellulosic materials for paper manufacture. Algae, a rapidly growing class of plant, with high resource conversion efficiency of have gained considerable interest from many research institutes and universities globally, research on macro and micro algae into products such as bioenergy, feed and pulp for paper. due to massive production of toxic chemical emissions such as chlorinated organic compounds, dioxin, black liquor etc., during chemical pulping process followed by the wood pulp papermaking, water and air pollution problems are always associated with conventional papermaking. Consequently, to avoid potential environmental damage caused by the conventional papermaking sources, the utilisation of other forest raw materials has become increasingly important in this field. Algae biomass was identified as new potential alternative scalable raw material for papermaking (Verma & Mehta, 2020).

Microalgae are also conveniently abundant sources of polysaccharides (cellulose in the cell wall of many green algae, and yet more physically interacting extracellular and intracellular polysaccharides from other taxonomic groups) which could be used as the fiber matrix for paper sheet making. Microalgal biomass has the benefit of being free of lignin, unlike wood pulp, which in papermaking is a glass ceiling to the production of papier-mâché, gyroscopes and other water “frustrating” products, until it is chemically and radiation-blitzed out of a large, bunch plasticine. Results from some experimental Papermaking tests have illustrated that ‘higher’, microalgae derived paper sheet products can be produced, with or without the addition of cellulose fibers, corn starch or other such banders, which perform on par with, or sometimes better than, current recycled papers grades (Kumar et al., 2019). The use of algae derived paper products for commercially advantageous biodegradable food packaging, seed germination paper, disposable service ware and artisanal stationery articles would be only logical.

IX. NATURAL COLORANTS FROM ALGAE

Phycocyanin (*Arthrospira platensis* (Spirulina)) is one of the most common commercial deep blue water soluble phycobiliproteins made in the world for use as a food and cosmetic colorant (Spirulina Blue)

(Sathasivam et al., 2019). But it has also been shown to have anti-oxidant, anti-inflammatory and hepatoprotective properties. *Haematococcus pluvialis* Astaxanthin--a red orange ketocarotenoid is currently the most profitable micro-algal pigment in the world with a value over US\$1 billion a year, mainly because it is used as an anti-oxidant nutraceutical and in the coloring of feed for shrimp and salmon Aquaculture (Borowitzka, 2018). Other micro-algal pigments are now beginning to be developed such as *dunaliella* (a source of beta-carotene), the group of diatoms(fucoxanthin), and some pigmented chlorophytes (chlorophyll). Attempts were also made in natural dyeing with microalgal pigments in the dyeing of cotton, silk and wool fabrics using the traditional metal mordants with reasonably good light and wash fastness in the laboratory. The synergy of algal pigment extraction techniques with the raw material sourcing, i.e. use of organic co-products (flower waste from marigold, hibiscus, rose and chrysanthemum flowers) represents a novel holistic approach to natural colorant synthesis that could be used in a more sustainable way. The large volume of floral waste obtained from the religious and ornamental flower industry in India could be very well used as a potential source of natural dyes from the abundance of natural flavonoids, flavanon-3,11-diol derivatives and carotenoid pigment available in these flowers, which can be extracted using aqueous and hydroalcoholic solvents and then effectively used as natural dyes in synergy with algal pigment fractions (Sathasivam et al., 2019).

X. BIOFUEL PRODUCTION

Along with the increased global need for cleaner, renewable, and sustainable energy sources, as well as rising ecological concerns over today ‘s dependence on fossil fuels, a new green energy monopoly has emerged, with an unsuspected contender based on a very ancient source: algae. Microalgae are considered third-generation biofuel sources as they have a rapid growth rate and photosynthesis efficiency and they produce high levels of lipids, which can be processed into biodiesel. Unlike other biofuel cultivation, microalgae allow processing on land that is unfit for traditional agricultures, they use wastewater and CO₂ thus saving water and avoiding displacing food crops, an attribute that stands out (Chisti, 2007;

Zhang et al., 2022). The biochemical composition of microalgae makes them a suitable candidate for biofuel production. Several microalgal species are capable of accumulating lipids (mainly triglycerides) in response to stress factors such as nitrogen depletion. Triglycerides are the primary source for the production of biodiesel. The sugars and proteins found in microalgae can be harnessed to make other forms of biofuels such as bioethanol and biogas (Rawat et al., 2013). When producing biodiesel from algae, several stages are involved: cultivation, harvesting and dewatering, lipid extraction and transesterification. During cultivation, microalgae are grown by utilizing open ponds or photobioreactors that provide control of environmental factors in order to optimize biomass and lipid productivity. Harvesting or dewatering of algal biomass has proved to be one of the most critical challenges since cells are small in size and at low concentrations in culture media. Extraction of lipids is usually achieved through solvent or mechanical extraction methods and subsequently processed through transesterification in order to produce biodiesel (Ghedini et al., 2021).

XI. PHARMACEUTICAL AND NUTRACEUTICAL APPLICATIONS

The diversity of bioactive secondary metabolites from the algae species has potential uses for the development of pharmaceutical drugs, food ingredients and cosmetic industries. The diversity of algal metabolites was partly through the metabolic processes of varying cellular structures and their numerous and diverse microbial communities with coevolved genetic exchange within. As a result, the huge potential of discovery of secondary metabolites for various beneficial purposes for human health such as anti-cancer agents, anti-infection, anti-viral agents, anti-inflammatory agents and anti-Oxidative properties was enormous. A number of algal species have been inducted into the functional food, nutraceuticals and pharmaceutical industries, for example, *Spirulina* species have been commercialised as health supplements of their high proteins, complete amino acids profile, rich vitamin B12 and micronutrients such as iron and gamma-linolenic acid (Wells et al., 2020).

XII. BIOPLASTIC AND PACKAGING

Algae have become an attractive renewable source for the synthesis of biodegradable bioplastics as well as materials for sustainable packaging combating the global concern with traditional plastics derived from petroleum. Microalgae or macroalgae are abundant sources of biopolymers such as polysaccharides (aging, agar, carrageenan), proteins and lipids from which biodegradable films and packaging materials can be derived. The polymeric material extracted from algae presents significant film forming ability and can be fabricated by film casting and extrusion processes among others for application in food packaging and others (Zeller et al., 2013; Khan et al., 2022). One significant benefit of the use of algae bioplastic is that it is biodegradable & environmentally friendly. Algal bioplastics are biodegradable by nature & serve as good replacement for synthetic plastics, which pollutes environment by their degrading byproducts & micro plastic generation. Growing of algae needs can be done on very minor amounts of land & fresh water & can make the use of carbon dioxide & waste water as media of growth (Khan et al. 2022). For packaging applications, fresh algae material could be used as barrier for oxygen & moisture. They can also be add-on by bioactive compounds which may be provide antimicrobial as well as antioxidant properties to food products (Khan et al. 2022). However, large scale commercial exploitation of algae-based bioplastics has not yet begun because of the various difficulties encountered like manufacturing costs, lower mechanical strength than conventional plastics and fluctuations in raw material composition. Additional work in the research laboratories pertains to the design and implementation of compounds and the enhancement of processing methods, in order to optimize the suitability of algae bioplastics as packaging materials. Having said all the above, algae-based packaging materials constitute a promising green alternation, with great future perspective.

XIII. COSMETICS AND PERSONAL CARE PRODUCTS

Marine algae have been identified as a vital natural resource of bioactive compounds for cosmetics and

personal cares applications because of the abundance of bioactive constituents contained within them including polysaccharides, proteins, lipids, vitamins and pigments. Both microalgae such as *Chlorella vulgaris*, *Spirulina platensis*, together with macroalgae (seaweeds) have been used extensively in skincare and other cosmetics products. The algae tissues contain antioxidant and essential fatty acids and minerals to retain the skin health, improve hydration and resist the environmental stress (Wang et al. 2015). Algal extracts can also be embedded in different skin care and cosmetic products such as creams, lotions, shampoos and even sunscreens, as they possess many bioactive properties. For example, carotene and phycocyanin are effective antioxidants, working on the prevention of free radicals, oxidative stress and skin aging. Marine algae derived sulphated polysaccharides are both anti-inflammatory and moisturizing, allowing them to be used in sensitive skin creams (Pereira et al., 2021).

XIV. CONCLUSION

In this review, the biological features, cultivation, harvesting and wide applications of algae has been systematically explored, confirming their status as a truly flexible and sustainable biotechnological platform. The biology of algae a fast growing, and biochemically rich and capable, nitrogen fixing, and environmentally diverse is precisely such that algae have application space in areas as others are unable namely agriculture, environmental, material, food and energy. In the agriculture area, algae (*Chlorella*, *Spirulina*, nitrogen fixing cyanobacteria) as biomassers, provide a viable alternative to chemical fertilization and pollution point sources, which has been scientifically proven safe, agronomically sound and benign to native biota, significantly improving crop yields, soil health and carbon storage. In the ecological front, degradation of textile effluents mediated by bioencapsulated algae and phytoremediation would offer a economic and scalable solution to the issues of highly polluted and contaminated effluent and in-situ enrichment of water bodies. The potential and emerging use of algae as a substrate for sustainable materials alginate-based yarn and textiles, biodegradable algae paper, natural pigments are clear examples of how algal biotechnology could spearhead the decarbonisation

and defossilisation of conventionally polluting industries. Commercialisation of these applications is rapidly increasing, propelled by regulatory requirements, consumer demand and the maturing of enabling technologies.

While considerable hurdles still exist in cost reduction for production, downstream processing, and persistent challenges in establishing clear regulatory pathways for novel algal products, the overlay of algal cultivation within circular bioeconomy practices using waste CO₂, wastewater nutrients, and non-arable land ironically offers an attractive economic and environmental case for continued research and development of algal biotech and lab-to-plant scale-up. The authors expect algae to assume a growing prominence within sustainable industrial systems in the coming decades.

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