Algae-derived Biomolecules: A Versatile Resource and Sustainable Solutions for India's Future

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Abstract

Over the past decade, algae have emerged as pivotal organisms, increasingly acknowledged for their profound ecological contributions and cutting-edge technological applications, particularly in the development of eco-friendly biomolecules. India's tropical climate and abundant sunlight create ideal conditions for large-scale algae cultivation, with oceans rich in microalgae, diatoms, and dinoflagellates. Of the 30,000 to 40,000 species, only a few are commercially utilized, but more can be explored for environmental, energy, and food security benefits. This review investigates algae-derived natural, carbon neutral biomolecules production and highlighting its scope and challenged in India It also outlines how algae can drive sustainability across sectors such as bio plastics, biofuels, food, cosmetics, and pharmaceuticals, along with emerging trends in the fashion industry like bio beads and bio leather. By lowering costs and reducing carbon emissions in algal biorefineries, these strategies contribute to a sustainable future. However, obstacles such as the energy-intensive production process and the need for optimized biorefinery pathways impede large-scale commercialization. Moreover, India's algae products market faces challenges, including low consumer awareness, difficulties in ensuring sustainable sourcing, and strict regulatory standards. Competition from conventional products, coupled with the need for continuous innovation to improve taste and versatility, further complicates market expansion.

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Introduction

A sustainable innovation wave is breaking over algae, a universal and photosynthetic organism that produces a plethora of valuable biomolecules with diverse applications in modern industries. From completely freshwater to marine habitats, a wide variety of algae exist. Large forms of algae like seaweed are found in various tropical and temperate coastal environments. Small forms of algae like the microalgae used for biofuels can thrive in many different freshwater and saltwater environments. The scientists' evaluations indicate that algae hold great promise for producing biofuels [1]. Indeed, if they thrive under ideal conditions (abundant sunlight, heat, and abundant nutrients), they can double their biomass in a short duration. The proteins present in unicellular algae *Chlorella* and *Spirulina,* though not as biofuel-friendly, could help support food supply and address malnutrition [2].

In food, pharmaceuticals, and cosmetics, polysaccharides such as agar, carrageenan, and alginate-made mostly from macroalgae-serve as thickeners, stabilizers, and gelling agents, reflecting the true potential of algae as a driver for sustainable advancement and a bioeconomy [3]. Additionally, algal biomass can be used to produce animal feed, reducing reliance on conventional fodder like soybeans, often linked to resource depletion and deforestation [4].

Algae also play a significant role in environmental remediation, such as wastewater treatment, utilizing nitrogen, phosphorus, and heavy metals as nutrients while simultaneously reducing pollutants and producing biomass for further applications [5]. Algae also contribute to carbon sequestration, with their ability to absorb large amounts of CO_2 during photosynthesis, making them a viable tool in mitigating climate change [6].

Recent Trends in Algal-Based Biomolecules

1. Algal Biofuels

Recent trends in algal-based biomolecules highlight their potential in biodiesel manufacturing through high lipid content, quick growth, and low land requirements. Studies have focused on developing lipid yield and increasing overall production efficiency through species selection (Table-I). Extensive research has been conducted on the lipid accumulation capacity of strains such as Chlorella sp., *Nannochloropsis* sp., *Scenedesmus* sp., and *Botryococcus braunii* [7]. Brazilian researchers have proven the viability of biodiesel production utilizing microalgae in open-pond systems, emphasizing its scalability. Genetic engineering advancements like CRISPR-Cas9 and metabolic engineering have allowed scientists to target critical enzymes in lipid production. biosynthesis pathway, such as acetyl-CoA carboxylase (ACC) and malic enzyme (ME), to increase lipid production [8-9]. Cultivation Optimization in which nutrient starvation (e.g., nitrogen or phosphate deficiency), high-light intensity cultivation, and two-stage systems have been used to increase lipid productivity [10-11]. Bioreactor Technology Advancements such as photo bioreactor designs, and tubular and flat-panel systems, have improved light utilization and scalability, lowering production costs [12-13].

Table 1: Algal Biofuels

Component	Biofuel Application	Co-Products
Lipids	Biodiesel (FAME production)	Lubricants, green solvents
Carbohydrates	Bioethanol, biogas	Bio-packaging, feedstock
Proteins	Residual biomass use	Animal feed, fertilizers
Pigments	-	Antioxidants, cosmetics

2. Algal Proteins and Nutraceuticals

Microalgae such as *Spirulina* and *Chlorella* are rich in essential amino acids, making them a complete protein source as cultivation requires minimal resources compared to conventional agriculture, making them particularly suitable for resource-scarce regions [14-15].furthermore these algae are integral to the production of functional foods and dietary supplements that support general health but also exhibit therapeutic benefits, enhanced immunity and reduced oxidative stress, addressing the demand for plant-based, nutrient-dense alternatives [16-17].In terms of personalized nutrition, the extensive biochemical diversity of microalgae enables the formulation of products that optimize health outcomes through targeted nutritional interventions [18].

3. Algal Polysaccharides

Algae-derived **hydrocolloids** like agar, carrageenan, and alginate are widely utilized in food, cosmetics, and pharmaceuticals for their gelling, stabilizing, thickening, and emulsifying properties, as well as in advanced applications like wound dressings and controlled-release drug formulations [19-20]. Bioactive polysaccharides from algae demonstrate immense potential in drug delivery systems due to their hydrogel-forming ability and immunomodulatory effects, making them ideal for functional foods and targeted therapeutics [21-22]. Algae-derived natural colorants such as chlorophyll, phycocyanin, and carotenoids are emerging as eco-friendly alternatives to synthetic dyes in food, textiles, and cosmetics, valued for their antioxidant, skin-health, and vision-support benefits [23-24]. Pharmaceutical applications of algae bioactive compounds include anti-inflammatory, anti-cancer, and antimicrobial effects, with chlorophyll derivatives, carotenoids, and phycocyanin demonstrating promise in drug development [25-26]. In India, algae-derived bioplastics, particularly from seaweed, are gaining momentum as sustainable alternatives to conventional plastics, with companies like Zerocircle using seaweed's regenerative and low-carbon properties to produce biodegradable materials, reducing plastic waste by up to 3,000 tons annually while supporting coastal economies in Tamil Nadu and Gujarat [27-28].

Table II: Algal Polysaccharides

Category	Component	Biochemical Component
Hydrocolloids	Agar	Polysaccharides
	Carrageenan	Polysaccharides
	Alginate	Polysaccharides
Bioactive Polysaccharides	Bioactive polysaccharides	Polysaccharides
Pigments	Chlorophyll	Pigments (chlorophyll)
	Phycocyanin	Pigments (phycobiliproteins)
	Carotenoids	Pigments (carotenoids)
Bioactive Compounds	Chlorophyll derivatives	Pigments (chlorophyll derivatives)
	Fucoxanthin	Pigments (carotenoids)
	Phycocyanin	Proteins

The Indian market for bioplastics is expanding due to government policies banning single-use plastics and promoting compostable alternatives. Despite these advancements, the sector faces challenges like reliance on imported raw materials, such as PLA and PHA. Boosting domestic production could further drive the adoption of bioplastics and strengthen the market's potential [29].

4. Environmental Applications

Wastewater Treatment

In India, algae-based wastewater treatment systems are growing more well-known for their capacity to support sustainability while effectively eliminating chemicals like nitrogen, phosphorus, and heavy metals. By effectively absorbing extra nutrients and breaking down organic contaminants, microalgae help keep water bodies from becoming eutrophic. These systems further improve their economic feasibility and environmental benefits by producing valuable by-products such as fertilizers and biofuels [30]. Research at IIT Hyderabad is driving this field's progress in India. The creation of economical bacterial-algal symbiotic systems for decentralized wastewater treatment is one of the projects. These systems concentrate on the removal of nutrients, the breakdown of organic carbon, and the removal of micropollutants. Pilot projects in gated communities have shown encouraging outcomes in terms of sustainability and usefulness. Furthermore, scaling these technologies for broader adoption is the goal of partnerships with foreign universities [31-32].

Carbon Sequestration

Algae are effective carbon sinks, which help to mitigate climate change. Large volumes of CO_2 are stored by microalgae during photosynthesis, which allows them to transform it into biomass at a rate that is far faster than that of terrestrial plants [33]. Industrial exhaust systems can be combined with algae to absorb carbon emissions and lower greenhouse gas emissions. A circular economy strategy can also be supported by using the biomass produced during this process to produce biofuel. Algae are a promising treatment for global warming due to their effectiveness and scalability in sequestering carbon [34].

Key Advancements in Algal Biotechnology

1. Genetic and Metabolic Engineering

Enhanced production of targeted biomolecules through CRISPR and synthetic biology

Algal biotechnology is being revolutionized in India by developments in synthetic biology and CRISPR-Cas9, which allow for precise genome editing improving the production of high-value chemicals, medicines, and biofuels. Research centres like the National Agri-Food Biotechnology Institute (NABI) and Jaypee University of Information Technology, together with businesses notably Reliance Industries, are spearheading initiatives to advance metabolic engineering methods for algae. These strategies, backed by government programs like the National Biopharma Mission and BIRAC incubators supporting entrepreneurs in genetic engineering and synthetic biology, involve creating artificial pathways to increase the output of molecules of commercial significance. These developments are in-line with India's emphasis on resource efficiency and sustainability, which are essential for tackling its environmental and economic issues [35].

Strain improvement for higher resilience and productivity

Strain improvement strategies, such as adaptive evolution and mutagenesis, are proving effective in enhancing algal species' resilience to environmental stressors, including temperature and salinity variations. In India, researchers are exploring these approaches to boost lipid accumulation and photosynthetic efficiency, critical for biofuel production and industrial applications. For example, the combination of adaptive laboratory evolution and mutagenesis has been employed to develop strains capable of thriving in fluctuating water conditions, often associated with industrial effluents, while maximizing lipid yields. These strategies are being paired with advanced genetic engineering to refine metabolic pathways and improve overall productivity, aligning with India's push for sustainable biofuel solutions [36-37].

2. Bioreactor Innovations

The focus of recent developments in algae cultivation methods is on expandable and economically viable solutions. Flat-panel and tubular photobioreactor designs have been adjusted to increase light penetration and nutrient consumption, which lowers operating costs and increases the efficiency of biomass production [38]. At the same time, open pond systems are being adapted for areas with lots of sunlight, such as India, where advancements in species selection, water circulation, and paddlewheel design have made large-scale production practical and profitable for uses like feedstock and biofuels [39]. These advancements are essential to overcome financial obstacles and move algae farming to industrial scales.

3. Integration with Circular Economy

By generating a single algal feedstock into several high-value products, including food additives, biofuels, and bioplastics, algae biorefineries reduce waste and improve resource efficiency-perfect examples of the circular economy [40]. Incorporating industrial waste streams, such as wastewater and CO_2 emissions, into algae culture systems is an important breakthrough in this field. In line with sustainable and environmentally friendly industrial practices, these waste products reduce pollutants and greenhouse gas emissions while providing algae with an affordable growing medium [41]. Algae's dual function in environmental restoration and resource efficiency highlights its potential as a pillar of sustainable development.

4. Digital Technologies in Algal Research

Algal research is undergoing a revolution driven by artificial intelligence (AI) and machine learning, which make predictive modelling possible for metabolic engineering, strain selection, and cultivation optimization. By decreasing the need for trial-and-error methods, these technologies boost output and quicken the development of algae bioengineering [42]. Additionally, by guaranteeing traceability, transparency, and quality assurance, blockchain technology is revolutionizing the supply chains for algae products. Blockchain promotes consumer trust and regulatory compliance by documenting each stage of manufacturing and distribution, especially in delicate industries like drugs and nutraceuticals [43].

Opportunities for Algal-Based Biomolecules in India

Considering its abundance of natural resources, pro-biotechnology regulations, expanding biotech sector, and prospects in the international export market, India holds great promise for the advancement of algae biotechnology. Regions like Gujarat, Tamil Nadu, and Andhra Pradesh are perfect for large-scale algae production in open ponds and high-value niche applications like nutraceuticals because of their vast freshwater systems and more than 7,500 kilometres of coastline [44]. Funding and collaborations for sustainable algae projects are provided by government programs such as the National Biotechnology Development Strategy and Mission Innovation, and the industry is further supported by subsidies for aquaculture and renewable energy [45].

India is well-positioned to export high-value algae products like spirulina supplements, carotenoids, and bioactive compounds, leveraging cost advantages to meet rising international demand for bio-based products [46]. The expanding biotech ecosystem, supported by programs like Biotechnology Ignition Grant (BIG) and BioNEST, encourages innovation and entrepreneurship, with startups investigating algae-based solutions like biofuels, bioplastics, and functional foods [47].

Conclusion

Algal-based biomolecules offer transformative potential for addressing India's critical challenges in sustainable energy, environmental conservation, and public health. These renewable resources align with national goals by reducing dependence on fossil fuels, mitigating pollution, and improving health outcomes through nutraceuticals. Algae-derived bioplastics and biofuels are revolutionizing sustainable manufacturing and energy solutions. Furthermore, innovative applications in the fashion industry, such as biobeads for sustainable jewellery and bioleather as an alternative to animal leather, highlight algae's potential in reducing environmental impact [48-49]. However, the widespread adoption of algal biotechnology necessitates strategic investments in R&D to tackle challenges such as hybrid cultivation system optimization, automation, and cost reduction. Innovations in these areas can enhance scalability and make algal solutions commercially viable.

Government support through subsidies, tax incentives, and streamlined regulations is pivotal to driving private investment and building an enabling ecosystem. Public awareness campaigns emphasizing the ecological and health benefits of algae-based products can encourage consumer adoption, while partnerships among industries, academia, and global initiatives can accelerate progress through shared knowledge and innovation. By embracing algal biotechnology, India could achieve its sustainability goals and emerge as a global leader in the bioeconomy, combining economic opportunities with ecological stewardship and technological advancements. This vision underscores algae's role as a catalyst for a sustainable future.

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