Algal bioplastics: current market trends and technical aspects

Neha Nanda1 · Navneeta Bharadvaja1

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Abstract
Plastics are undebatably a hot topic of discussion across international forums due to their huge ecological footprint. The onset of COVID-19 pandemic has exacerbated the issue in an irreversible manner. Bioplastics produced from renewable sources are a result of lookout for sustainable alternatives. Replacing a ton of synthetic plastics with biobased ones reduces 1.8 tons CO2 emissions. Here, we begin with highlighting the problem statement—Plastic accumulation and its associated negative impacts. Microalgae outperforms plants and microbes, when used to produce bioplastic due to superior growth rate, non-competitive nature to food, and simultaneous wastewater remediation. They have minimal nutrient requirements and less dependency on climatic conditions for cultivation. These are the reasons for current boom in the algal bioplastic market. However, it is still not at par in price with the petroleum-based plastics. A brief market research has been done to better evaluate the current global status and future scope of algal bioplastics. The objective of this review is to propose possible solutions to resolve the challenges in scale up of bioplastic industry. Various bioplastic production technologies have been comprehensively discussed along with their optimization strategies. Overall studies discussed show that in order to make it cost competitive adopting a multi-dimensional approach like algal biorefinery is the best way out. A holistic comparison of any bio-based alternative with its conventional counterpart is imperative to assess its impact upon commercialization. Therefore, the review concludes with the life cycle assessment of bioplastics and measures to improve their inclusivity in a circular economy.

Graphical Abstract

Keywords Microalgae · Cyanobacteria · Biopolymer market · Life cycle assessment · Bioplastic · Genetic engineering

Extended author information available on the last page of the article
Introduction

Plastic is an indispensable item in today’s era. Plastic industry is a key contributor toward any country’s economy due to its huge revenue generation and wide array of end products across diverse areas. Population explosion has led to an ever increasing demand for plastic commodities. On an average, an annual demand of 140 million tons of plastic requires 150 million tons of fossil fuel as an input. If this trend continues, estimates are that by 2050, plastic will outweigh all the fish in the sea. Petroleum-based plastics have long been used and offer convenience, versatility, durability and affordability due to well-established processes and mature technology. But they are a threat to the ecosystem as they consequently accumulate in the environment, being non-biodegradable. They are recalcitrant and leach into water bodies to form hazardous chemicals. Their open burning generates more than one gigaton CO$_2$ emissions. Microplastics are becoming a matter of growing concern due to their ubiquitous presence in water, food and air samples as well as inside the human body. They reduce the carbon capture ability of phytoplanktons. About 8 million tons of plastic leak into the oceans annually. This can be alleviated by redesigning packaging materials. Plastic debris in the oceans and seas affect aquatic species through ingestion, entanglement and suffocation, eventually leading to death in many cases (Quero and Luna 2017). Plastic waste is piling up at an annual rate of $25 \times 10^6$ tonnes globally, completely jeopardizing the solid waste management system. Hence, it is rightly termed as ‘White pollution,’ and it will not be an exaggeration to say that we live in a plastisphere (Balaji et al. 2013). The gravity and urgency of the situation can be well understood by the facts presented in Fig. 1.

Many countries have recently banned single-use plastics (SUP) like disposable bottles, straws and polybags. While crude oil prices are at an all time high and our fossil reserves are fast depleting, need of the hour is to look for sustainable and greener alternatives. Extensive research efforts are being carried out in this direction. As a result, biopolymers like Polyhydroxyalkanoates (PHA) and Polylactic acid (PLA) have recently gained popularity. They offer the dual advantage of being biodegradable and at par with the synthetic plastics in mechanical and physical properties. They decompose about 60% or more into CO$_2$, water and compost by the surrounding microbes within 3 months, while petrochemical-based plastics take 1000 years for the same (Saratale et al. 2020). Figure 2 highlights some of the noticeable pros of bioplastics. Bioplastics can be classified as either biodegradable, bio-based or both. Being biobased means that it has originated from renewable biomass like plants. However, the property of biodegradability is decided by the chemical composition of a polymer and not by its source. Likewise,
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the time of biodegradation is decided by the environmental factors like temperature and microbial consortium in the vicinity. There are three major classes of bioplastics, (i) Fossil fuels-based plastics but biodegradable. E.g., Polybutylene Adipate Terephthalate (PBAT), (ii) Bio based but non-biodegradable (Drop-ins). E.g., Bio-based Polyethylene, Polypropylene, Polyethylene-terephthalate (iii) Bio-based as well as biodegradable plastics. E.g., Polylactic acid (PLA), Polyhydroxyalkanoate (PHA), Polybutylene succinate (PBS) (European Bioplastics 2020). This review focuses on bioplastics that are both, biobased and biodegradable.

The demand for single use plastics (SUP) skyrocketed as the highly infectious disease COVID-19 hit the globe. This was in lieu of the safety measures and changing patterns in consumer behavior. Personal protective equipment (PPE) kits, gloves, masks, eyewear, face shields, sanitizer bottles were used in huge amounts by frontline workers and general public alike. According to a WHO report, the monthly global usage of gloves, goggles and face masks could roughly be around 76, 1.6 and 89 million, respectively (Chaib 2020). These will dramatically contribute to medical waste and microplastic pollution since they are made of non-biodegradable plastics like polypropylene (PP), polyethylene, polystyrene, polycarbonate and polyyacrylonitrile. One surgical mask has 4.5 g of PP while one N-95 has 9 g of it. Moreover, it has been reported that 10-30 W electricity is consumed and 59 g CO₂ is released in the manufacture of one mask (Selvaranjan et al. 2021). Medical trials and vaccination drives utilized syringes in numbers large enough to circle the globe multiple times, if laid end-to-end. To put things in perspective, generation of global herd immunity would require 800–1000 billion syringes for vaccinating 60% of the world population. Rapid antibody and RT-PCR testing procedure utilize SUP supplies. Sequencing of one suspected sample generates 37.27 g plastic waste. According to the data till August 2020, 15.4 M kg of plastic waste has accumulated due to vigorous COVID-19 testing worldwide. Hence, the pandemic opened up another potential area for bioplastic utilisation. Conversion of PLA resins and filaments into masks and medical equipments like face shield frames by 3-D printing is underway (Patrício Silva et al. 2021). Polyhydroxyalkanoate (PHA), polylactic acid (PLA), Polyethylene 2,5-furandicarboxylate (PEF) and PEF-co-PLA are fit for use in PPE suits due to their appropriate physiochemical properties. Their use can reduce the negative impact on environmental viability caused by their petrochemical equivalents. However, it would require scalability, capital, safe design, well-structured policies and financial assistance at the government level to be able to do so for visible impact.

Artificial intelligence has offered many innovative solutions to reduce and manage plastic waste. AI technology is optimizing product and packaging designing to reduce the amount of plastics used. Deep neural networks are a reliable and cheap method of predicting structural properties that directly impact a material’s biodegradability. These prediction models can perform millions of computations to give the best potential biopolymer structure. Hence, AI solutions can identify “smarter” plastics that are durable and easily recyclable (Novak et al. 2021). Satellite imaging and machine learning is being used to detect oceanic plastic patches and clean them. Real-time monitoring of recyclable plastics in mixed waste is helping in faster and accurate sorting. Real-time analysis of ambient operating conditions in composting facilities is possible through wireless Internet of Things (IoT) sensors. Corrective actions can be taken immediately from anywhere if thresholds are breached (Riley et al. 2021). With the help of nanotechnology, lightweight aluminum and steel have been developed to reduce the dependence on SUP items. Antimicrobial nanomaterial coating on perishable products can reduce the need of plastic packaging.

The objective of the contribution is to provide consolidated information about algal bioplastics and their contribution toward circular economy. Based on literature review, three research questions were formulated: Are algal bioplastics superior to other plant-/animal-derived plastics? What are the recent technological advancements in their production processes? What is the current status of start-ups producing algal bioplastics and what are the challenges they face in scaling up? The review attempts to address these questions and propose possible solutions to the challenges encountered by the bioplastic industry.
Sources of bioplastics

Plants and animals

So far, first and second generation feedstock is being commercially employed for bioplastic production. This includes sugarcane, cassava, lignocellulosic biomass, corn, straw, woodchips, paper, sawdust, vegetable fats and oils, recycled food waste, etc. Naturally processed polysaccharides and proteins like starch, cellulose, gluten, casein, etc., are also turned into bioplastics (Coppola et al. 2021). Chemical modification or fermentation of plant or animal-derived lipids and sugars is also performed for bioplastic production (Sudhakar et al. 2021). The co-products of animal processing like skins, tallow, hides, etc., are a natural, low-cost carbon source for producing biodegradable films and PHA. Being easily available in plentiful amounts, they can remarkably cut down production cost while at the same time put this waste to good use. Animal-derived proteins like gelatin, collagen from broken casings, keratin, etc., are well suited for producing compostable films and PHA. Being easily available in plentiful amounts, they can remarkably cut down production cost while at the same time put this waste to good use.

Bioplastic production using algal biomass is still in the infancy stage. Substitutes of agro-crops are being sought after because using them for bioplastic production will raise the following concerns in the long run. First, they will compete with human food and animal feed. It is anticipated that the world will demand 70% more food, fodder and fiber in near future as per the data of Food and Agriculture Organization (FAO). Microalgae and cyanobacteria surpass this problem. Second, growth of plants requires arable land, expensive fertilizers and large quantities of water. In comparison, microalgae is easily adaptable since it can grow on wastewater resources and remediate them at the same time (Kumar and Bharadvaja 2021). They demand minimal energy and nutrient input and contribute to circular and bio-economy. They grow thirty times faster than food crops without requiring much supervision and disease management. In the upcoming decades, urbanization and population rise will spring up the food demand and lessen the agricultural land area which will further intensify the problem. Third, plants need long duration for growth in quantities that are exploitable and profitable on an industrial level (Balaji et al. 2013). On the contrary, microalgae possess higher rate of photosynthesis and biomass yield. Some of them double in a matter of 6 h. Last but not the least, cell wall disruption for biopolymer extraction from plants is difficult due to layers of impenetrable, tough cell wall. This requires phytomass to be pre-processed by cellular disintegration, pelletizing and enzymatic hydrolysis in attempt to remove the recalcitrant lignin. It not only complicates the procedure but also incurs additional processing cost of about 140 EUR per kg of theoretically hydrolysable lignin. There is additional energy requirement to provide high pressure and temperature for disintegration. Oil extraction from seeds is another cost-intensive step. Skipping these steps can cut down the cost of production by more than 50% and make bioplastic price competitive. Hence, algae as a raw material emerges as a lucrative choice (Škapa and Vochozka 2019). Low PHB expression level in plants is also a matter of concern. Genetically manipulating plants by introduction of biosynthesis genes to obtain greater yield is being attempted by many researchers. (Zeller et al. 2013).

Aforementioned are some latest studies where plants have been used as a starting material for bioplastic production. Arikan et al. utilized potato peels to generate potato peel bioplastic that showcased complete biodegradability within a month along with better water absorption in comparison with commercial bioplastics (Bezirhan Arikan and Bilgen 2019). Starch-based bioplastics have been made from Manihot utilissima (cassava) peels using modified PVA and citric acid to improve its mechanical properties. Chong and colleagues made fiber-reinforced bioplastics by putting corn waste to use. Corn starch provided the sachharide part that formed the matrix and the waste functioned as the reinforcement material (Chong et al. 2021). In an attempt to resolve the large-scale stubble burning and prevent associated pollution, rice straw has been viewed as another potential feed.

Microbes

Microbial species are also being investigated for the potential of bioplastic production, in place of terrestrial crops. It has been found that Alcaligenes eutrophus accumulates as much PHB as 85% of the cell dry weight, while recombinant E.coli cells can produce up to 70–90% PHB content. Bacteria like Azotobacter beijernickit, Pseudomonas, Micrococcus, Bacillus, Rhodococcus,Ralstonia eutrophina and Rhodococcus produce PHB naturally in response to excess carbon presence and nutrient limited conditions. The extent of production depends on the microbial strain, concentration and type of substrate provided and physiochemical factors like temperature and pH (Singh Saharan et al. 2014). The prime drawback of using bacterial fermentation for producing biopolymers is costly production, 48% of which is attributed to the carbon source. In order to sustain heterotrophic microbial growth, external aeration and carbon source supply must be ensured which makes the process expensive when compared to conventional polymers. Bioplastic production using autotrophic cyanobacteria is an economically wiser choice since it would significantly reduce...
the feed costs and the simpler genetic makeup would make genetic engineering for bioplastic accumulation easier. All it requires is sunlight and the cheapest carbon source, CO₂. It can survive with these minimal requirements under adverse environmental conditions. However, the purification costs for both will be comparable. Efforts are being made in the direction of reducing raw material cost and securing reliable and scalable supply of cheap carbon sources. *Ralstonia eutropha* is an autotrophic bacteria that produces significant amount of PHB, intracellularly, using CO₂. It has reportedly produced 80% PHB content of dry cell weight (DCW) using animal or plant oils, alcohols, simple sugars and organic acids. *Methylobacterium* uses methanol as carbon substrate to produce PHB at lower price (Priyadarshi et al. 2014). In a latest study by Saratale et al., *Ralstonia eutropha* (ATCC 17,699) and the most noxious weed, *Eichhornia crassipes*, were exploited for PHB production. PHB accumulation of 73% of DCW and titer of 7.30 g/L were obtained (Saratale et al. 2020).

**Algae**

In an attempt to sustainably produce plastics while simultaneously maintaining an undisturbed supply of food and feed, researchers have explored the marine world and found microalgae to be a promising and viable alternative. Sea-weeds are rich in polysachharides like carrageenan, agar and alginate, that are the starting materials for producing bioplastics (Sudhakar et al. 2021). Algal breeding can be done on industrial effluents and sewage water without stressing existing water reserves for biomass production. Microalgae has excellent capacity to reduce the Chemical Oxygen Demand (COD) of wastewater by utilizing and assimilating the organic and inorganic nitrogen (ammonia, nitrate, etc.) and carbon for growth. It also helps in recovering phosphorus in a sustainable and economically feasible manner (Stávková and Maroušek 2021; Maroušek and Maroušková 2021). This gives microalgae an extra edge over other sources used for bioplastic production. It can now comply with zero waste policy and also upcycle existing wastes and residual microalgal biomass into valuable products in biorefineries. PHB production using microalgae will offer maximum societal benefits at reasonable cost and no negative environmental impact as opposed to their petrochemical counterparts (Ansari and Fatma 2016; Coppola et al. 2021). Microalgae is one of the main reasons why oceans are the largest CO₂ sink. Yet another reason for algae to be an ideal source of bioplastic production is that they directly capture the atmospheric carbon and trap it into biopolymers. For e.g., *Chlorella vulgaris* soaks the maximum amount of CO₂ and is widely studied for bioplastic production. Algae can capture up to 960 kg of CO₂ per ton (Rahman and Miller 2017). There is abundant space available for microalgae since about 3/4th of the earth’s surface is water. Thus, utilizing them for this purpose will convert the waste biomass into a universal commodity and at the same time mitigate climate change (Balaji et al. 2013). The small size of micro-algal cells facilitates a scalable production since there are no added costs of protein isolation and pre-treatment.

Oil prices, feedstock cost and policy support are decisive factors in the cost-competitiveness of bioplastics. Exchange rate is a crucial indicator of fluctuations in international crude oil prices. Artificial neural network-based models accurately predict the exchange rate and inflation-deflation, which affects the purchasing power of consumers (Vochozka et al. 2020). From monetary perspective, a study estimates the algal biomass production cost in an open raceway pond to be around 1.7 to 1.9 USD/kg of dry weight (DW) under ideal conditions. Considering inflation adjustments, that amounts to 2.1–2.2 USD/kgDW at present. Here, biomass productivity of 10 g/m²/day was assumed for the study period of 300 days. In contrast, productivity of 1–4 g/L has been reported in the literature when algae is cultivated in a closed system like a photobioreactor (PBR) (Slade and Bauen 2013). The production cost of one short ton of dry weight algae in a PBR is around USD 1137. According to a latest research, the cost of producing PLA using cassava starch as a starting material is 2,890 USD/t PLA. However, if cassava root is used, it reduces to 2710 USD/t PLA due to byproduct (gypsum and flour) generation that reduced the net cost. Hence, this clearly indicates that following a holistic and integrated approach can make the process profitable (Wellenreuther et al. 2022). Similarly, a recent study reported the production cost of PHA to be 2.2–5.0 euros per kg. When PHB is produced from microalgae, cultivation and harvesting operations constitute 62–72% share in the total cost. (Reichert et al. 2020). Thus, the choice of open cultivation system is preferable on a commercial scale. Algal biorefineries accommodate the high production cost by utilizing the high value products like pigments, produced in multiple product streams. Also, utilizing waste heat and solar energy instead of natural gas can compensate for the energy demands of the production unit.

**Algae-based bioplastics**

Polyactic acid (PLA) is a thermoplastic having characteristics equivalent to polyethylene (PE), polystyrene (PS) and polypropylene (PP) in addition to being biodegradable. It is derived from lactic acid condensation or lactide polymerization where lactic acid is preferably produced by bacterial fermentation due to separate production of its D and L isomers. Its thermal properties and tensile strength are superior to synthetic polymers and it has been investigated for its recyclability. PLA decomposes completely into
organic matter, CO₂ and water. Upon hydrolysis or alcoholicysis, PLA gets regenerated as lactic acid. It is degraded in an industrial composting facility and does not give off any toxic byproducts upon oxygenation (Plavec et al. 2020).

Fiber-reinforced PLA composites are a popular choice for green packaging of food products on account of easy fabrication, affordability, non-toxicity, thermal stability, flavor and aroma resistance and heat sealing ability at lower temperature. According to a research, CO₂ emissions of PLA are 1600 kg per ton while that of PA, PET and PP are 7150, 4140 and 2740 kg CO₂ per ton. This suggests that PLA production is a closed loop system with lower carbon emissions (Karamanlioglu et al. 2017).

Polyhydroxyalkanoates are a family of 150 types of different biodegradable polymers classified according to the number of monomeric units they possess. Two of the most popular kinds are the short chain PHAs—Polyhydroxybutyrate (PHB) and Poly(hydroxybutyrate-co-hydroxyvalerate) PHBHV consisting of 3HB and 3HB-3HV units as monomers, respectively. They are polyesters accumulated in the inclusion bodies in microbes and microalgae as carbon and energy reserve under unfavorable conditions. PHAs are believed to solve the unending issue of plastic litter since they possess inherent thermoplastic properties and mechanical properties similar to petrochemical plastics and are thus referred to as bioplastics. However, their physical properties vary depending on the type and number of monomers they are made up of (Priyadarshi et al. 2014). Their renewable nature presents them as attractive targets for the plastic industry. They can be produced by fermentation using plant sugars and oils as carbon and energy sources. When exposed to enzymes like PHA hydrolases and depolymerases, secreted by microbes, they get broken down into water and carbon dioxide. The time required for complete decay varies from some weeks (in anaerobic sludge) to years (in sea). Table 1 summarizes the factors that positively and negatively affect PHA synthesis in cyanobacteria.

**Polyhydroxybutyrate (PHB)**

It is a biopolymer synthesized by prokaryotes in the form of intracellular storage compound and belongs to the PHA family. It is majorly composed of 3-hydroxyvalerate (3HV) along with 3-hydroxyhexanoate (3HH) as minor components. It exists as an amorphous fluid intracellularly but becomes crystalline upon extraction. PHB was first discovered by a microbiologist named Lemoigne in *Bacillus megaterium* in 1966 by chloroform extraction. Its tensile strength and thermal properties are similar to synthetic plastics. It is an environment-friendly option and suitable replacement of petroleum-based plastics due to its thermoplastic processibility, hydrophobicity, high degree of crystallinity, optical purity, gas barrier properties and high melting temperature of 175 °C. It can degrade under home-composting conditions unlike other bioplastics that require industrial composting facility. PHB fibers are elastic and hard but have low elongation at break (EAB) which can be improved by blending it with PHBV or polyhydroxyvalerate (PHV) to form a co-polymer, either biologically or chemically (Saratale et al. 2020; Kamravamanesh et al. 2018a, b).

When microalgae are encountered with nitrogen or phosphorus deficiency, the intracellular accumulation of PHB is favored due to the high NADPH pool. ATP production, electron transfer and protein synthesis are downregulated. Certain proteins (like alkaline phosphatase enzyme) are synthesized that assist in acclimation of the cell to such starvation conditions. The entire pathway of PHB and PHBV synthesis is illustrated in Fig. 3a and b (Balaji et al. 2013; García et al. 2021). It occurs with the help of three critical

Table 1  Schematic overview of Supporting and inhibiting factors for cyanobacterial PHA synthesis (Koller 2015)

| Positive/Negative | Supporting Factors | Inhibiting Factors |
|-------------------|-------------------|-------------------|
| Positive          | Deprivation of exogenous Nitrogen, Phosphate, Sulfur | Supply of exogenous Nitrogen, Phosphate, Sulfur |
|                   | Overall reduced protein synthesis | High intracellular pool of ADP, AMP, NADP⁺ (Low cellular energy charge) |
|                   | Upregulation of acclimation-associated proteins | High activity of PHA depolymerases, phosphotransacetylase |
|                   | High intracellular pool of ATP, NADPH and Acetyl-CoA (High cellular energy charge) | Citrate, α-ketoglutarate, DCMU (3-(3,4-dichlorophenyl)-1,1-dimethylurea) |
|                   | High activity of RuBisCo, β-ketothiolase and acetoacetyl-CoA reductase | Optimized gas exchange (promotes biomass growth) |
|                   | Reduced carbon compounds like sugar and acetate |                              |
|                   | Illumination, CO₂ |                              |
|                   | Limited gas exchange |                              |
|                   | Carbonyl cyanide 3-chlorophenylhydrazone (inhibitor of oxidative phosphorylation), DCC (Dicyclohexylcarbodiimide), azaserine, MSO (L-Methionine-DL-sulfoximine) |                              |

References

Koller (2015); García et al. (2021)
enzymes and involves three PHB precursors. It starts with glucose being converted to two molecules of acetyl CoA via glycolysis. Then, the phaA encoded enzyme, β-Ketothiolase, condenses them into a single molecule of acetoacetyl-coA which is further reduced by NADPH dependent acetoacetyl–coA-reductase (encoded by the gene phaB) to D-3-hydroxybutyryl CoA. Finally, the third enzyme PHA synthase (encoded by the gene phaC) links D-3-hydroxybutyryl CoA molecules via ester bonds to form the biopolymer, Polyhydroxybutyrate (PHB) (Balaji et al. 2013; García et al. 2021).

**Market research and economical aspects**

At present, bioplastics comprise only 1% (more than 365 million tons) of the huge multi-million dollar plastic market (European Bioplastics 2020). Bioplastic market is gaining fast attention as businesses are being pressurized globally to ‘Go Green’ and carbon neutral. But an annual growth rate of 30% indicates that bioplastics are likely to remarkably influence the supply chain of plastics globally. Commodity thermoplastics ($1540–$2200 USD metric tonne−1), biodegradable resins ($2640-$5500 USD metric tonne−1), and engineered resins ($1540 and $8800 USD metric tonne−1) can all be replaced by algal bioplastics. This large market share of bioplastics can make algal biorefineries economically scalable and feasible (Research and Markets 2021). The global bioplastic market, by product includes Polylactic acid, Thermoplastic starch, Biopolyamides (nylons), Polyhydroxyalkanoates, Biopolylols/polyurethane, Cellulosics, Biopolytrimethylene terephthalate, Biopolyethylene, Biopolylethylene terephthalate and Polybutylene succinate (Research and Markets 2021). PHA production is estimated to rise tenfold over the next five years (European Bioplastics 2020). The global bioplastic market, by application, includes many sectors like construction, electronics, textile, among others. Of these, the packaging and consumer durables segment are projected as the most profitable.

Notable multinational companies across various sectors have diversified their product portfolio and incorporated

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**Fig. 3**  
(a) Polyhydroxybutyrate (PHB) synthesis pathway from glucose  
(b) Poly(3-HydroxyButyrate-co-3-HydroxyValerate) synthesis pathway from propionic acid. (Chemical structures taken from PubChem)
bioplastic in their product packaging. Some notable ones are supermarket chains like Walmart, Carrefour, Sainsbury, Billa, Spar and Hofer (BCC 2021). Danone has adopted a sugarcane-derived bioplastic material as packaging material for its yogurt containers (activia, volvic, etc.) to cut down the product’s carbon footprint by 55% and significantly reduce the company’s ecological footprint (Casey 2015). The consumer electronics giant Fujitsu is using corn-based PLA for biodegradable packaging of integrated circuits to achieve energy and CO₂ emission reduction by 18% and 11%, respectively. In the automotive sector, Toyota, Mercedes and Ford have emerged as examples. Ford has collaborated with McDonald’s to use chaff-based bioplastics in headlamp housing for cars. The proposed biomaterial will boost fuel economy, being 20% lighter than plastics and consuming 25% lesser energy for production. Heinz and coca-cola have partnered to incorporate 100% recyclable sugarcane-based PET in product packaging. Ford is using this PlantBottle technology for door panels, seat covers and carpets in car interiors. In the food and beverage industry, Nestle is leading the front with its vision to achieve a 33% reduction in virgin plastic packaging by 2050. In this regard, it is using PLA, bio-PET and bio-PE as packaging material for pet food (Purina ONE), potable water (Vittel) and beverage caps, respectively. Moreover, Lavazza’s coffee capsule made of bioplastic that is completely biodegradable and compostable. An Israel-based company, TIPA Corp, develops biofilms for handbags that decompose within 3 months when home-composted Sweden-based MNC, IKEA has also gone sustainable by launching ISTAD, a resealable bioplastic bag which is predicted to largely reduce company’s carbon footprint by saving 75,000 barrels of oil, annually. The personal care beauty brand Pangea uses sugarcane-derived biopolymer for product packaging. PUMA has shoe soles made up of 60% bioplastic (APINAT Bio) content. Samsung is now using starch or sugarcane-based PLA, PBS and PBAT for making protective bags for kitchen and home appliances. Lastly, 95% of all the packaging material used at Ecover is bioethanol-derived PE reducing its annual CO₂ emissions by 2500 tons (Perchard 2016, India Berry 2021).

Biobased and biodegradable plastics form 58.1% of the total bioplastic market as shown in Fig. 4 (European Bioplastics 2020). Its present production (2020) is around 1227 thousand tonnes which has been predicted to grow to 1800 thousand tonnes in the next 5 years (Fig. 5) (European Bioplastics 2020). Majority of production takes place in the USA, Europe and the Asia–pacific (APAC) region, where new product launches, acquisitions and contracts would guarantee lucrative opportunities for the stakeholders in the upcoming years. The global bioplastics and biopolymers market is predicted to grow from USD 10.7 billion in 2021 to USD 29.7 billion by 2026, at a compound annual growth rate (CAGR) of 22.7% (Markets And Markets 2021).
USD 2/kg of its petrochemical counterparts. This is because the technological processes are not yet advanced enough to reach economies of scale and reduce the polymerization cost for biopolymers (Markets And Markets 2021). However, a decreasing trend in pricing over the years is favored by factors mentioned in Table 2 (BCC 2021) that will gradually make bioplastics cost competitive. As far as the land use for growth of sufficient feedstock for bioplastic produce is

**Global production capacity of bioplastic in 2021-by market segment (in % )**

![Global production capacity of bioplastic in 2021-by market segment](image)

**Fig. 5** Global production capacity of bioplastic in 2021 (by market segment)

**Global production capacities of bioplastics (2019-2025)**

![Global production capacities of bioplastics (2019–2025)](image)

**Fig. 6** Global production capacities of bioplastics (2019–2025)

**Table 2** Internal and external factors encouraging the growth of bioplastic market (BCC 2021)

| Driving factors                                                                 | Restraining factors                                      |
|-------------------------------------------------------------------------------|----------------------------------------------------------|
| Internal factors                                                              | External factors                                         |
| Advanced technical properties and functionality                               | High consumer acceptance and demand                      |
| Possibility of being scalable and cheap                                       | Environmental awareness                                   |
| New and economical recycling methods                                          | Rising prices of fossil resources                        |
| Rigorous R&D                                                                  | Dwindling fossil fuel reserves                            |
| Development of novel biomaterials and biopolymers                             | Rise in the number of government investments              |
|                                                                                | Government regulations and obligations                     |
| High cost compared to conventional plastics                                    | Nascent upstream technology                               |
| Environmental awareness                                                       | Performance and design inertia                            |
| Rising prices of fossil resources                                            | Availability of substitutes                                |
| Dwindling fossil fuel reserves                                                |                                                         |

[^1]: Springer
concerned, it is negligible (0.015%) compared to the vast area of arable land worldwide (1.4 billion ha). Estimates are that it will rise to 1.1 million ha (0.02% of total area) by 2025.

**Key players**

Prominent players in the global bioplastics and biopolymers market include NatureWorks (US), Braskem (Brazil), BASF (Germany), Total Corbion (Netherlands), Novamont (Italy), Biome Bioplastics (UK), Mitsubishi Chemical Holding Corporation (Japan), Biotec (Germany), Toray Industries (Japan), and Plantic Technologies (Australia) Tianan Biologic Material (China). Others include Bio Fab NZ, Danimer Scientific, Ecovative Design LLC, Eranova, Kaneka, Mango Materials, Newlight Technologies, Oimo, Biome bioplastics and Uluu (Research and Markets 2021). Among these, some significant start-ups and established companies that have incorporated algal bioplastics in their product chain are aforementioned.

Algix performs bioprospecting of the aquatic biomass in algal blooms and converts the species harboring polymerization capacity into end products by injection molding and extrusion compounding. The high-performance bio-resins are then scaled up for production. It generates an annual revenue of USD 27 million (Algix 2010). Loliware works on the foundation of SEA technology (Seaweed-based, Emission-Avoiding, Alternatives to Paper and Plastic) which is a regenerative and carbon-sequestering input. It manufactures flexible films, pulps and other substitutes to single use plastics from seaweed. It developed an edible hyper compostable straw that can decompose on land and water (Loliware 2015). Notpla (Skipping Rocks Lab’s) is a London-based start-up that exploits seaweed for making home-compostable packaging materials. Its edible and biodegradable water sachets—called Ohoo—are made up of a material that naturally disappears within a few weeks (Notpla 2014). Evoware is an Indonesia-based firm that shapes and presses dried seaweeds into bags, cups and wraps, manually. The resulting material is smooth on the outside, rough on the inside and has a shelf life of two years even in the absence of preservatives (Evo & Co. 2016). AMIM is a Japanese company researching on a product named ‘Agar Plasticity’ made using waste shell ash and agar harvested from red marine algae as the main component. When disposed away, the agar in the material help enhancing the water retention of soil and eventually degrades over time (Amam 2015). AlgoPack is a French company turning seaweeds into cups. It is focused on the toxic, invasive brown algae Sargassum, which is a threat to public health. It rather transforms it into rigid bioplastics (AlgoPack 2010). Cereplast, a company founded in 2001, develops compostable and biobased resins. It majorly uses corn, potato, tapioca and wheat as raw material. Cereplast Algae Plastics have 50% algal content and 50% polyolefins for binding. But it envisions to create 100% algae-based resins in near future (Cereplast 2001). Soley Biotechnology Institute produces bioplastic from Spirulina dregs that are leftover after extracting useful products from Spirulina.

The Indian bioplastic market is expected to grow at a CAGR of 23.91% to reach USD 754.648 million by 2025 from USD 208.475 million in 2019. The reasons for this logarithmic growth are environmental consciousness, reduced costs, sustainable businesses, technology stabilization and profit-yielding biopolymers like PHA, PLA and starch blends (Knowledge Sourcing Intelligence 2021). The key market players include Ecolife, Plastobags, Earthsoul India, Truegreen, Geelimitti, Ecobuddy. Envigreen is a Bengaluru-based company, founded in 2012 with an annual turnover of Rs. 25 to 30 crore and a production capacity of 300 metric tonnes. Its aims at making non-toxic, bioplastic using natural starch, vegetable oil derivatives and vegetable waste (EnviGreen Biotech India Pvt Ltd 2016). Pappco is a Mumbai-based start-up that manufactures microwave-friendly glasses, bowls and plates from bioplastic extracted from algae, microbes and plants (sugarcane, wheat straw, and bamboo) (Pappco greenware 2010).

**Conversion technologies: algal biomass to bioplastic**

**Biocomposites**

**Additives—plasticizers and compatibilizers**

Microalgae are very small in size and are highly sensitive to moisture. So, mixing them with materials that complement their properties makes them cheaper, highly processible and widely applicable. Acetone and sodium sulfite are solvents used for washing the biomass before the blending process (Cinar et al. 2020). Plasticizers are non-volatile organic compounds that are mixed with bioplastics to improve their stretchability, processability, biodegradability and thermoplasticity. They may have a biological origin or they may be derived from petroleum. When they are added at a high temperature to the polymer, they enter the intermolecular spaces, lubricate them and increase the molecular mobility of the polymer chains by decreasing the secondary interactions like hydrogen bonding (Sudhakar et al. 2021). The more efficient the plasticizer, the softer the resultant biocomposite. Examples include octanoic acid, sorbitol, PEG, 1,4-butandiol and glycerol which is the most used plasticizer. (Cinar et al. 2020). The number of hydroxyl groups in the plasticizer, its compatibility with the biopolymer, its type and concentration are decisive factors for a successful product. Sudhakar et al. (2021) synthesized biofilm using...
the red seaweed *Kappaphycus alvarezii* with PEG-3000 as a plasticizer that can prove as a game changer for the plastic industry (Sudhakar et al. 2021). Balqis et al. (2017) investigated the effect of various concentrations of plasticizer on biofilm characteristics and reported that biofilm thickness, and water vapor permeability vary directly with plasticizer concentration, while solubility shows an inverse relationship. A suitable plasticizer at an optimum concentration produces biofilms with desirable mechanical properties (EAB of more than 10% and tensile strength between 10 and 100 MPa) for commercial use. (Ili Balqis et al. 2017).

Compatibilizers are compounds that are added while making of polymer blends to enhance the consolidation, mechanical and physiochemical properties. One portion binds to the biopolymer, while other binds to the synthetic polymer. Some of its examples are diethyl succinate, poly(ethylene-co-glycidyl) meth acryloyl carbamate and maleic anhydride. The choice of compatibilizer is governed by the polymer blend in consideration (Zhu et al. 2017; Cinar et al. 2020). Dianursanti et al. (2018) varied the concentration of Maleic anhydride and concluded that compatibilizer can remarkably enhance the homogeneity and flexibility of the PVA-Chlorella vulgaris biofilm. They found that with increase in compatibilizer amount, the tensile strength and elongation also increase. This is because the hydrophobic anhydride group of compatibilizer bonds with the hydrophilic hydroxyl group in the microalgae giving rise to additional bond formation between the two that strengthens them. As far as the morphological characteristics are concerned, the previously rough film that lacked compatibilizer became smooth, compact, dense and homogenous upon its addition due to better solubility of PVA and *Chlorella*. Homogeneity contributed to enhanced flexibility, reduced stiffness and high percentage elongation. Compatibilized product also exhibited better dimensional stability, an essential requisite in the packaging industry (Dianursanti and Khalis 2018). Similar conclusions were presented by Dianursanti et al. (2019) who studied the effect of varying concentration of maleic anhydride compatibilizer on PVA-Spirulina platensis blends (Dianursanti et al. 2019). Zhu et al. (2017) demonstrated that maleic anhydride-grafted PBS to biomass as a compatibilizer enhanced the tensile strength and decreased the degradation temperature of the product (Zhu et al. 2017).

**Production techniques**

There are several methods by which microalgae-polymer blends can be made. They are summarized in a stepwise manner in Fig. 7 (Cinar et al. 2020). Compression molding is the commonest way of turning microalgae into bio-composites in closed molds with a stationary and mobile plate. It involves placing a mixture of algal biomass, additives and polymers in a mold and then subjecting it to high temperature and pressure briefly. The temperature could be anywhere in between from 130 to 160 °C, pressure between 20 kPa and 10 MPa and a time range of 3 to 20 min. Molds come in different shapes and sizes for making all kinds of prototypes like rectangular bars, films and slabs (Cinar et al. 2020). Ciapponi et al. (2019) produced bioplastic using wheat gluten, plasticizers (glycerol, octanoic acid and 1,4-butanediol) and microalgae as a biofiller. They produced 1 mm thick slabs by placing the mixture in an aluminum mold and exposing it to a temperature of 120 °C, pressure of 40,000 kPa for 10 min in a hot press. The resulting film had a tensile strength of 4.9, elongation at break (EAB) of 22% and toughness of 1 MJm⁻³(Ciapponi et al. 2019). Zhu et al. (2017) used melt blending and compression molding in combination to produce poly(butylene succinate) (PBS)/Spirulina (1:1) composites with maleic anhydride as compatibilizer, water as plastisizer and glycerol as co-plasticizer. Microalgae-PBS mixture was melt blended at 130 °C for 6 min, dried and finally compressed at 130 °C under 10 MPa pressure for 3 min. The resultant bioplastic showed a tensile strength of 25 MPa, melting point of 66.85 °C and was 55% crystalline (Zhu et al. 2017).

In solvent casting, additives, polymers and microalgae are mixed in a suitable solvent and cast dried into films. In a study by Fabra et al. (2018), three microalgae species (*Nannochloropsis, Scenedesmus* and *Spirulina*) were melt mixed with corn starch, glycerol and water at 130 °C and 60 rpm for 4 min to form a homogenous mixture. The mixture was compression molded under a pressure of 207 MPa at 130 °C for 4 min to form thermoplastic films having tensile strength of 13.5 MPa with spirulina and elongation % of 2.1 with Nannochloropsis (Fabra et al. 2018). Solvent casting was also employed by Abdo and Ali (2019) to synthesize bioplastic using three algal species—*Microcystis aeruginosa, Chroococcus turgidus* and *Haematococcus pluvialis*. The biomass was mixed with sorbitol, gelatin and glycerol, heated at 95 °C, casted in a pan and dried to result in final PHB product. It had a tensile strength of 1.62 MPa and EAB of 530% (Abdo and Ali 2019). Melt mixing technique was used in the production of *Spirulina platensis*(56%)-PVA(27%) biocomposite by Gozan and colleagues. Maleic anhydride and glycerol were the compatibilizer and plasticizer, respectively. The biopolymer showcased properties comparable to fossil fuel-based plastics—tensile strength of 2.72 MPa along with an EAB of 66%. Glycerol-MA were mixed into a viscous suspension by heating at 120 °C for 20 min with constant stirring. The melted mixture was put in a glass mold, heated at 100 °C for 15 min and cooled into the desired bioplastic film (Dianursanti et al. 2018). Hot molded Chlorella vulgaris/PVA plastic blend was prepared by Dianursanti et al. (2018) where maleic anhydride-graft and *Chlorella*-glycerol were well mixed at 120 °C and molded. It was observed that increasing maleic anhydride concentration improved the
morphology from rough to smooth, tensile strength from 31.27 to 4.14 MPa and elongation from 10.86 to 13.00%. Thus, it was evident that compatibilizer made the biocomposite more elastic and homogenous (Dianursanti and Khalis 2018).

Injection molding is a cheap, quick and simply automated process for mass producing materials in various shapes and sizes. The only major challenge is to fully and properly accommodate the melted polymer mix into the micro-nanostructure before it cools and solidifies owing to the high surface area to volume ratio (Maghsoudi et al. 2020). Torres et al. (2015) combined the biopolymer PBAT with residual microalgae biomass (RMB) through twin extrusion followed by injection molding. The two components were extruded together at 100 rpm while being exposed to a temperature of 100 °C for 2 min. Subsequently, the mixture was injection molded at 30 °C. Biomass plasticization was done with glycerol and urea in the extruder at 100 °C. The resultant biopolymer had a tensile strength of 21 MPa along with 600% elongation. Optimum results were reported with 20% RMB, 30% glycerol and 7.5 (parts per hundred rubber) phr of urea. (Torres et al. 2015). Twin screw extrusion is a scalable method to convert bio-derived powders and granules into extruded homogenous plastic products with a good conversion rate. The microalgae additive mixture is directly plasticized at high temperatures with a residence time of few minutes inside the extruder (Maghsoudi et al. 2020). It was exploited for producing C. reinhardtii 11-32A-starch.
biocomposite with a melting point of 159 °C and water content of 2.34% (Mathiot et al. 2019).

Genetic engineering

Genetic engineering is easy to perform on simple, single-celled phototrophs like microalgae and cyanobacteria due to no cell differentiation as in complex plants. It has been successfully reported in PHA synthesizing C. reinhardtii, Synechococcus sp. and Synechocystis sp. From Table 3, it is evident that cyanobacteria Synechocystis sp. PCC 6803 is widely researched for enhancement of PHA production via the genetic engineering route. The reasons behind it are its well-studied metabolic pathways, optimized growth conditions and proper characterization. The integration process of a foreign gene in this cyanobacteria is also established (Hein et al. 1998). Cyanobacteria and microalgae can be genetically modified by various ways. Random mutagenesis method leads to a transversion in the algae genome when it is exposed to a physical mutagen like UV radiations or chemical mutagens like ethyl-methanesulfonate and ethidium bromide (EtBr). The limitation is that it is time intensive since it requires screening of the exposed population of cells for selection of those with desired mutations and phenotypic expression (Kamravamanesh et al. 2018b).

Metabolic engineering is the science of exploring metabolic pathways and understanding the role of enzymes and molecules involved in them. In the context of bioplastic research, metabolic engineering of algal and cyanobacterial strains has been attempted to introduce PHB production pathways, enhance the PHB yield, produce new PHBs and to utilize cheaper and a variety of substrates to achieve economies of scale. Heterologous transformation of cyanobacteria with PHB synthetic genes (3-ketothiolase, acetoacetyl-CoA reductase and PHB synthase) of R. eutropha has been reported (Balaji et al. 2013). Synechococcus sp. PCC7942 is one such cyanobacteria that does not produce PHB indigenously. So, its recombinant strain was produced by transforming it with the above genes. Moreover, PHB productivity was enhanced by the incorporation of a stronger promoter and supplementation of acetate. These R. eutropha genes have been transformed into E.coli because of its high growth rate even at risen temperatures and simple cell structure. Due to this, E.coli that naturally lacks PHB synthesis ability can produce PHB in bulk which can be purified economically by simple cell lysis methods. Through genetic engineering, it will be possible to make algal bioplastics commercially more feasible by reducing its production cost by use of alternative substrates and new extraction methods (Balaji et al. 2013). A merger of genetic engineering and molecular microbiology can assist in better understanding bioplastic properties through analysis of genetic and metabolic blueprints. Recombinant microalgae also exhibit the potential for high PHB accumulation due to their high reproductive capacity, ease of handling and maintenance and rapid growth in simple media (Hempel et al. 2011).

Influence on sugar catabolism also affects PHB accumulation. Osanai et al. in their study overexpressed sigma factor sigE in the control strain (GT) to activate sugar catabolic genes in the recombinant strain GOX50. It was concluded that manipulating carbon metabolism was more effective than heterologous transformation in increasing the PHB yield. Inverse metabolic engineering (IME) is the identification of phenotypes of interest and their encoding genes. This approach was used by Tyo et al. who created a library of Synechocystis PCC6803 mutants by inserting transposons at particular loci. It was observed that the mutants with ORF sll0461 disruption accumulate higher levels of PHB intracellularly. sll0461 codes for the proA gene that synthesizes a key enzyme of proline biosynthetic pathway- γ-glutamyl phosphate reductase. Proline functions as a protective osmolyte, in the absence of which, stress conditions trigger higher PHB production (Tyo et al. 2009). There have been studies which found that upregulation of PHA synthase activity was ineffective in increasing the PHA content in transgenic strains. Lau et al. (2014), in their study, obtained increased PHA accumulation through upregulation of photosynthetic enzymes and proteins participating in the electron transport chain. The higher production potential of CcsNphT7BCn was linked to overexpression of ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCo) which provided efficient supply of essential precursors of PHA production. These high producing strains did not show higher concentration of PHB synthesizing enzymes, indicating that it is not their low levels that limit PHA production. Instead the total carbon flux drives PHA biosynthesis (Lau et al. 2014). CRISPR-Cas9 system of gene editing can be used in future to overexpress PHB biosynthetic genes. It is already being analyzed in Chlamydomonas reinhardtii (Kamravamanesh et al. 2018b).

However, this promising technology comes with drawbacks of its own. Needless to say, any external intervention in the genetic makeup of an organism can make it a potential threat to the environment, when exposed. So these transgenic microalgal or cyanobacterial strains are cultivated indoors under strict control and vigilance and not in outdoor open pond systems. Genetic transformation can boost the intracellular PHB accumulation only up to a certain threshold, above which any more of it is detrimental for the cellular metabolism. If this limit is low in many species, the entire process will go in vain. Wild-type cells show better reproducibility and fitness than transgenic ones. Thus, the screened cells may lose the recombinant gene after a few generations. To overcome this, antibiotics are added to sustain the genetically modified cells under a
**Table 3** PHB production using genetic engineering technology

| Recombinant microalgae          | Genetic modification                                                                 | Culture conditions                        | PHB content | References                  |
|--------------------------------|--------------------------------------------------------------------------------------|--------------------------------------------|-------------|-----------------------------|
| *Phaeodactylum tricornutum*     | Insertion of *R. eutropha* H16 PHA synthesis genes                                    | Autotrophic; NO$_3^-$ induced PHA production | 10.6%       | Hempel et al. 2011          |
| *C. reinhardtii* cc-849         | Introduction of phbB and phbC genes from *R. eutropha*                                | Photoautotrophic, batch                     | 6 µg/g      | Chaogang et al. 2010        |
| Recombinant cyanobacteria       |                                                                                      |                                            |             |                             |
| *Synechocystis* sp. PCC 6714    | Random mutagenesis                                                                    | Photoautotrophic                           | 30%         | Kamravamanesh et al. 2018b  |
| *Synechococcus elongatus* PCC 7942 | Insertion of *C. necator* phaA and phaB genes, *E. coli* and *Pseudomonas putida*     | Photoautotrophic                           | 1.2 g/L     | Ku and Lan 2018             |
|                                | thioesterase gene tesB and *Streptomyces* sp. acetoacetyl-CoA synthase gene nphT7    |                                            |             |                             |
| *Synechococcus elongatus* UTEX 2973 | Insertion of *C. necator* phaABC operon                                               | Photoautotrophic                           | 16.7%       | Roh et al. 2021             |
| *Synechocystis* sp. PCC6803     | Overexpression of heterologous phosphoketolase xfpk (phosphoketolase) from *Bifidobacterium brev phosphoketolase* and double pta (phosphotransacetylase) and ach (acetyl-CoA hydrolase) knockout | Photoautotrophic                           | 12.4%       | Carpine et al. 2018         |
| *Synechocystis* sp. PCC6803     | Deletion of slr1829 and slr1830 (encoding PHB polymerase)                             | Photoautotrophic; phosphate limitation, 21 days batch | 533.4 mg/L  | Wang et al. 2013            |
| *Synechocystis* sp. PCC 6803 (GOX50) | Overexpression of SigE (RNA polymerase sigma factor)                                 | Natural exhaustion of N$_2$ sources        | 1.4 mg/100 mg | Osanai et al. 2013         |
| *Synechocystis* sp. PCC 6803 (Δgdc mutant) | Inactivation of gdc gene encoding glutamate decarboxylase                         | Photoautotrophy,                           | 5.5%        | Monshupanee et al. 2019     |
| *Synechocystis* sp. PCC 6714 (mutant MT_a24) | Random UV mutagenesis: Point mutation in phosphate-specific transport system integral membrane protein A (PmA) | Nitrogen and phosphorus starvation          | 37%         | Kamravamanesh et al. 2018a |
constant selection pressure. These antibiotics are hazardous for public health (Pulz and Gross 2004).

**Algae species used for bioplastic production**

**Microalgae**

The successful commercial exploitation of microalgae for bioplastic production requires identification of the most promising and efficient species and taking into consideration the physiochemical factors that affect the production pathways. (García et al. 2021). The *Chlorella* species is a freshwater green alga comprising of 51 to 58% protein of the total dry cell weight. Its thick cell wall imparts it better crack resistance and thermal stability than *Spirulina*. *C. sorokiniana* is widely used in making starch blends because of its high gelatinization temperature of 110 °C. There are many studies on these two microalgae due to their small cell size, which makes them desirable in film and fiber market where particle size is a crucial determinant. In addition, their small size and high protein content make it easier for them to be converted into bioplastic on a large scale, in a cost-effective manner without generating much waste in pre-treatment. They are also well-investigated species for their production methods since they are being utilised for quite some years in the nutraceutical industries. Apart from that, both *Chlorella* and *Spirulina* have the potential to remediate the wastewater they grow in and recycle the CO₂ bubbled into the growth medium in the form of higher biomass productivity. Bioplastics made wholly of *Chlorella vulgaris* (CV) are brittle irrespective of the species used, but when plasticized, CV bioplastics exhibit better plastic-like behavior (yielding and initial modulus) than *Spirulina*. It is probable that compatibilized *Chlorella* blends can outperform compatibilized *Spirulina* blends in terms of performance. Hydrogen ions in *Chlorella* allow blends to be produced without any gaps. *Chlorella*-PVA and *Chlorella*-PE composites are used for food packaging purposes. This difference in blending behavior of the two can be explained by their varying amino acid composition (Cinar et al. 2020; Zeller et al. 2013; Diannursanti et al. 2018).

**Cyanobacteria**

Blue green algae are unicellular organisms found in fresh, marine and brackish water. They accumulate the homopolymer of PHB as intracellular granules under stressful environment. They reserve it as a surplus carbon and energy source to be metabolized later under unfavorable conditions. They are a preferred host system due to their ability of photoautotrophy and survival in minimal nutrient supply. They are powerful CO₂ scavengers and significantly reduce greenhouse gas emissions (Sharma and Mallick 2005). By far, 137 cyanobacterial strains from 88 species and 26 different genera have been screened for PHB content. Out of these, 134 strains showed decent PHB concentration under normal conditions, while 63 strains showed extraordinary PHB accumulation, when subjected to nitrogen, phosphorus and potassium deficiency. PHB is a carbon-rich metabolite. So 26% of the total carbon required for its synthesis is fixed when cells are nitrogen starved and pre-grown photoautotrophically. However, 74–87% of it is contributed by intracellular carbon recycling. The time of addition of acetate has significant impact on PHB levels. Acetate supplementation in the beginning along with nitrogen depletion supplies 44–48% of the total carbon required for PHB synthesis, doubling the accumulated PHB amount. In contrast, if it is added in between, it can only supply 34% carbon. So a check on nutritional status during the formation of PHB precursors is vital in obtaining high PHB accumulation in the cytoplasm of cyanobacteria (Dutt and Srivastava 2018). PHB accumulation was first reported in 1966 in the cyanobacteria *Chlorogloea fritschii* (Kaewbai-ngam et al. 2016). Hein et al. found that *Synechocystis* sp. PCC6803 has inherent PHB synthase activity and is a well-suited PHB expression system due to easy genetic modification and spontaneous transformability. *Spirulina* species is a cyanobacteria found commonly in highly alkaline freshwater. But it can also be cultivated in all types of water including fresh, brackish and seawater. It possesses 46% to 63% protein content. Blend properties of *Spirulina* are superior to *Chlorella* making it more advantageous commercially. *Spirulina* can also be a good filler due to its high protein content. *Scenedesmus almeriensis* is another blue green algae found in freshwater and brackish waters with a potential of PHB accumulation (García et al. 2021). *Calothrix Scytonemicola* is a photoautotrophic freshwater cyanobacteria that converts CO₂ into the biopolymer PHB (Kaewbai-ngam et al. 2016). In a research by Sharma and Mallick, it was concluded that the cyanobacteria *Aulosira fertilissima* synthesizes PHB in roughly 10% of the carbon utilization as opposed to bacteria (Sharma and Mallick 2005). This shows that cyanobacteria can cut the cost of oxygen and carbon supply, making the whole production process cheaper than many other PHA producing strains. Other microalgae used in the bioplastic industry include, *Neochloris oleoabundans*, *Nannochloropsis gaditana* (Torres et al. 2015), *Phaeodactylum tricornutum*, *Aphanthece sp.*, *Gloeotece sp.* and *Synechococcus sp* (Hempel et al. 2011). Table 4 lists some of the wild type microalgae and cyanobacteria that inherently produce PHB.
Life cycle assessment of bioplastics

Life cycle assessment (LCA) provides a holistic view of the environmental and socioeconomic efficiency of bioplastics by evaluating their entire life cycle based on different impact categories. Impact categories are indicators for LCA quantification and include ecotoxicity, human toxicity, water and land use, eutrophication, acidification potential, global warming potential, ozone depletion potential, etc. Choice of the right impact categories is essential to a meaningful LCA. LCA allows a consumer to weigh the pros and cons of a product and take informed decisions. Different analytical approaches give different outcomes. Cradle to gate (resource acquisition and production), cradle to grave (acquisition, production, use and end of life phase) and gate to grave (use and EOL phase) are three methods of LCA based on system boundaries. Resource acquisition in case of plastics involves oil extraction and refining, while for bioplastics, it involves plant cultivation and associated agrochemical inputs. Out of the these, cradle to grave provides near accurate estimation of results as it takes consumer interaction, disposal and waste management system into consideration (Rosenboom et al. 2022). The contribution of bioplastics toward a circular economy is illustrated in Fig. 8 (European Bioplastics 2020).

Using the ‘distance to target’ approach, a bioplastic and its petrochemical counterpart can be simultaneously compared for their environmental impact. Cradle to gate greenhouse gas emissions for petrochemical based plastics is 1.8–3.55 ton CO₂/ton, while that for bioplastics is 0.4–1.3 ton CO₂/
In a cradle-to-grave LCA by Moretti et al., it was found that if PLA cups are composted/recycled and produced using renewable electricity, their environmental footprint would be lesser than polypropylene cups even after examining the land use change impact category (Moretti et al. 2021). Chávez et al. assessed the life cycle of different bioplastics according to their effects on health and environment. This included genetic modification of feedstock, use of agrochemicals during its cultivation, exposure to hazardous additives and solvents during its manufacturing, generation of toxic by-products, water use and energy use efficiency. Based on this, they highlighted the sustainability improvements of biopolymers in comparison with their conventional counterparts and concluded that PHA and PLA are preferable choices over other biopolymers (Álvarez-Chávez et al. 2012). Growing of feedstock for bioplastics requires land which leads to changes in land use pattern if plants are used as a feedstock. Pesticides and fertilizers used also negatively impact the acidification and eutrophication impact category. So even a 5% global increase in production of first generation bioplastics would not be sustainable. Microalgae cultivation instead can be done in limited area with water recycling and no competition with food to address this issue (Ita-Nagy et al. 2020). Latest reviews regarding LCA of bioplastics have underlined the inadequacy of LCA methodologies, insufficient data availability, biased choice of impact categories and absence of consequential modeling. Bioplastics outperform petroleum based plastic in some impact categories, while in others, the latter are superior. Cradle-to-gate cycle of PHB suggests that it is more beneficial than polypropylene even after considering the large energy and water requirement, eutrophication potential and chemical toxicity. This is because the decrease in global warming potential, ozone depletion potential, and abiotic depletion compensates the increase in other impact categories for bioplastics. Thus, it was successfully concluded in the study by Harding et al. that when compared in overall indices, PHB is more eco-friendly and sustainable than PE and PP (Harding et al. 2007).

End-of-life (EOL) is a key component of LCA. Among various options, mechanical recycling has been widely concluded as the most suitable disposal method for bioplastics with least carbon footprint. Anaerobic digestion, landfiling, composting and incineration of 1 kg PLA generate 2.2 kg, 1.6 kg, 1.5 kg and 1.7 kg CO₂ respectively, as opposed to 0.62 kg CO₂ in case of mechanical recycling (Rosenboom et al. 2022). It is cheaper, compared to chemical recycling, and does not emit obnoxious gases as in incineration. Landfiling causes leachate seepage and uncontrolled methane release upon biodegradation. For effective anaerobic digestion of bioplastics to occur, their degradation time should be within 15–30 days. PHB fulfills this criteria while PVA, PLA and PCL fail to do so (Bátori et al. 2018). One major sustainability issue of bioplastics like PLA is that they are not home compostable and require elevated temperature conditions (> 50 °C) of industrial composting unit to degrade quickly and completely. The compostability rate of bioplastics depends on its thickness which is 68 μm and 3000 μm for PBS and PLA, respectively (Reichert et al. 2020). Stepping up bioplastic production would mean land transformation and use of more agrochemicals for cultivation that can translate into negative consequences. PHB and PLA show higher levels of eutrophication, acidification and GHG emissions, respectively, in comparison with some fossil fuel-based plastics. First and second generation bioplastics present major concerns of ecotoxicity, deforestation and soil quality degradation during their production (Rosenboom et al. 2022). To mitigate these burdens, algae which is viewed as waste can be resourceful when converted into new generation bioplastics.

To assess the sustainability of bioplastic, certain schemes and ranking criteria must be defined. Developing predictive models like BioWin and Biodegradability evaluation and simulation system (BESS) that suggest consumers the best bioplastic based on application and EOL options available are needed (Reichert et al. 2020). Responsible consumer behavior can go a long way in deciding the success of any eco-friendly product. Improper labeling, lack of knowledge, standards and certifications and information overload are reasons of confusion and ineffective sorting among end users. Moreover, there is no established large-scale sorting facilities for bioplastics due to their limited production. Hence, bioplastics end up in landfills as opposed to the intended EOL treatment route which fails its purpose. Artificial intelligence (AI) and Infrared spectroscopy guided optical sorting at material recovery facilities help to differentiate between visually indistinguishable bioplastics and plastics. AI assists in their application-based segregation of as opposed to composition. However, these are expensive, complex and presently limited (Morris and Hicks 2022). Improved sustainability can be achieved by optimizing production processes through technological advancements and powering production units utilizing renewable energy.

**Conclusion and future outlook**

The escalating consumer demand for plastic is intensifying the problem of plastic litter. It can only be mitigated by shifting to greener and sustainable alternatives like biodegradable plastic. However, the industrial-scale use of algae and other waste biomass for bioplastic production is still far from real as first and second generation biomass remain as the dominant raw material till date. Bioplastic, rightly called as the ‘Plastics of future,’ has the power to relieve the over-burdened waste management system. But some hurdles need to be overcome, in order
to make this platform widely accessible and economically feasible. Extensive research efforts are being carried out in the direction of bioengineering, improved downstream processing and constructing mathematical or network models of PHA production pathways. The most attractive approach in this regard is a microalgal biorefinery that integrates multiple value-added product streams (food, feed, pharma products, biofuel) and wastewater remediation as to extract maximum benefit from a single batch of biomass. It improves the techno-economics of microalgae cultivation on a commercial level. However, ways to minimize the use of additives in the process need to be further investigated since they render the product unsuitable for application in the medical and food packaging sectors. Various options like nutrient limitation, preculture supplementation and parameter optimization are being explored to get maximum PHB yield from cyanobacteria. In addition, innovative, cheaper and more efficient conversion technologies need to be researched. For instance, PHB purification from microalgae and carbon source are two significant cost drivers in the production process. CRISPR-Cas9 has been recently employed for producing superior strains through genetic engineering and needs further studies to be fully developed. There is a need to put the global plastic challenge into better context by incorporating a holistic life cycle perspective into research efforts. A complete techno-economic analysis would aid in better understanding the larger picture of bioplastics in the vast plastic industry, that are emerging as a promising alternative to their conventional counterparts. LCA of bioplastics is an under-researched area that needs better understanding, when considering the gate to grave approach. Development of bioplastics that degrade under mild conditions effectively can boost their applicability. Economic constraints are a major factor in determining the upscaling of the mentioned current technologies that are successful at the laboratory scale. Conclusively, the current market trend and technology improvisations in the area suggest a bright future for start-ups in the algal bioplastic avenue. It is now only a matter of few years that they will soon hit the market and become a popular choice among people within no time.

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Authors and Affiliations

Neha Nanda1 · Navneeta Bharadvaja1

Navneeta Bharadvaja
navneetab@dce.ac.in

1 Plant Biotechnology Laboratory, Department of Biotechnology, Delhi Technological University, Shahbad Daulatpur, Main Bawana Road, Delhi 110042, India