Discover Environment

Review

Microalgae: an emerging source of bioplastics production

Anli Dino A[1] · **Kishore G**[2]

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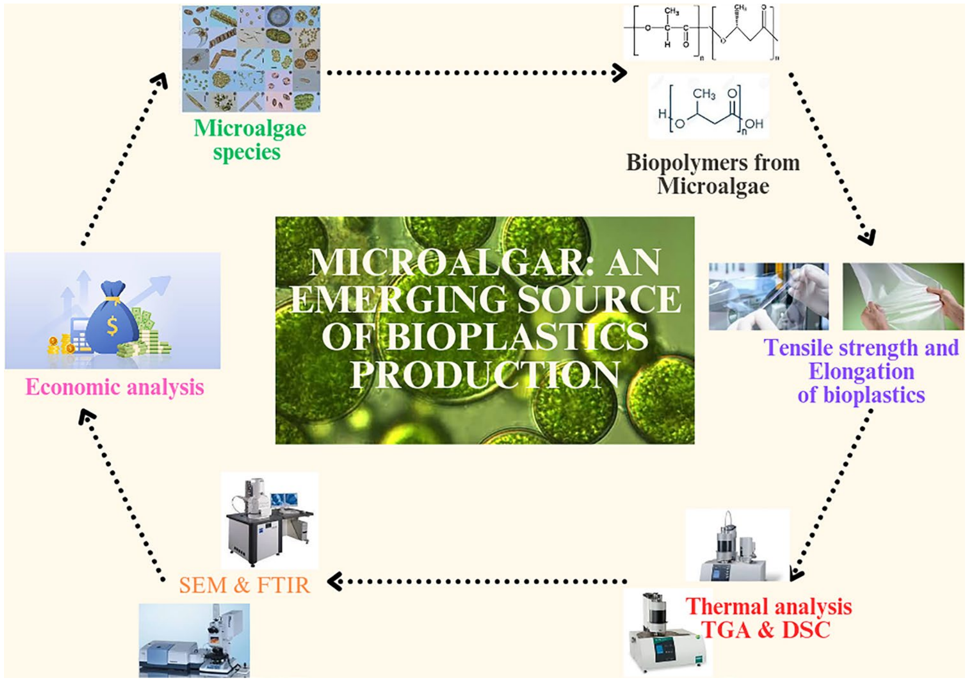
Abstract
Bioplastics has gained attention as a sustainable alternative to traditional petroleum-based plastics. Microalgae have become one of the more promising and environmentally benign feedstocks to produce bioplastics. The goal of this in-depth review study is to address both the possibilities and the difficulties of manufacturing microalgae-based bioplastics. The review begins by discussing the negative impacts that commercial plastics have on the environment, pollution, and resource depletion. It then introduces the idea of bioplastics and discusses their importance in reducing the previously mentioned issues brought on by plastics. The article discusses the distinctive qualities of microalgae as a sustainable biomass source, noting their rapid development, high lipid content, and low need for both land and water. The various production processes and procedures used to create microalgae-based bioplastics are thoroughly explored. To determine whether the mechanical, thermal, and barrier qualities were appropriate for different applications, they were examined. Biodegradability and shelf life are factors in environmental impact assessments that highlight their potential to help mitigate the negative effects of plastics. Economic viability is a crucial factor that is examined through cost analyses and discussions of the prospects and incentives for market growth. To provide a glimpse into the future of microalgae-based bioplastics as a sustainable material option, current trends and innovations are emphasized. This review advances our knowledge of microalgae-based bioplastics in the race for a more sustainable plastics industry by offering a fair evaluation of their advantages, disadvantages, and uses.

✉ Anli Dino A, anlidino@gmail.com; Kishore G, drgk002@gmail.com | [1]Department of Biotechnology, St. Joseph's College of Engineering, Chennai, India. [2]Department of Biotechnology, Karpaga Vinayaga College of Engineering and Technology, Chengalpattu, India.

Graphical Abstract



Keywords Bioplastics · Microalgae · Commercial plastics · Biodegradable plastics · Sustainable plastics

1 Introduction

Plastics are hydrophobic, inert substances made of covalently bound, long-chain molecules with high molecular weight. The organic composition of plastics gives them malleability, moldability, strength, and durability. These synthetic plastics are made from crude oil, natural gas, or petroleum sources. Plastics are inexpensive, lightweight, and chemically stable. It is now more common in our lives in various aspects. Plastic is utilized in many industries, including packaging, textiles, electrical applications, and the manufacture of items such as water bottles, cups, soft drink cans, boxes, toys, and trays. The plasticizers used in plastics, such as bisphenol-A, phthalates, polystyrene, and antimony, increase the health risk and prevent them from degrading. Since they are not naturally degraded, they have significant effects on human health, the environment, and aquatic life. They can be broken down using heat, light, chemicals, water, and microorganisms, but none of these processes work well. The chlorine component in plastics can contaminate the soil by penetrating it. Animals, fish, and other marine species may die after ingesting thrown plastic, which can also have an impact on ecology. In this era of growing environmental hazards, environmentally friendly alternatives to conventional plastics have garnered attention on a global scale. In assessing the environmental impact of bioplastics, Table 1 provides a comprehensive comparison between bioplastics produced from algae, bacterial bioplastics, and conventional plastics.

Biodegradable, environmentally friendly plastic made from natural resources is known as bioplastic. The supplies include sugarcane, potato starch, corn, wheat, soybeans, milk protein, collagen, gelatin, algae, and other microorganisms [1]. Competition between land and water results from the production of bioplastics from these plant sources [2]. Additionally, the method of making bioplastics is highly challenging. These sources create bioplastics, but they have lower mechanical and water resistance qualities. Because the bioplastics made from these crops are unstable and cause issues with the food economy, microalgae are being used as a source for making bioplastics. As a result of their quick development, high photosynthetic efficiency, and ability for CO_2 fixation, microalgae are employed as a source to create bioplastic. Microalgae are suitable for making high-quality bioplastics due to their lipid, starch, protein, cellulose,

Table 1 Comparison between bioplastics derived from algae with bacterial bioplastics and conventional plastics [37–45]

S.NO	Properties	Algal bioplastics	Bacterial bioplastics	Conventional plastics
1	Molecular weight	20–95 kDa	20–60 kDa	10–300 kDa
2	Thermal analysis	10–30 ºC	40–60 ºC	80–100 ºC
3	Degree of crystallinity	92–95%	60–80%	10–80%
4	Degradation duration	65–90 days	90–120 days	Half-life of 5–250 years in landfills, compost, soil conditions
5	Transparency/appearance	Transparent	Transparent	Transparent
6	Fermentation/cultivation duration	1–4 weeks	1–4 weeks	Not applicable
7	Water absorption	Low	Low	Low
8	Cost considerations	3.8 US $/Kg	3.8 US $/Kg	1.6 US $/Kg
9	Toxicity and safety	Generally safe	Generally safe	Potential hazards
10	Renewability of resources	Renewable	Renewable	Non-renewable
11	Recyclability	Less chance of recyclability	Less chance of recyclability	Recyclable
12	Density	1.397 g/cm^3	1.397 g/cm^3	0.96 g/cm^3

hemicellulose, and lignin concentrations. Currently, starch, cellulose, Polyhydroxyalkanoates (PHA), Polyhydroxybutyrate (PHB), Polylactic acid (PLA), Polyethylene (PE), Poly vinyl chloride (PVC), and protein-based polymers are used to make bioplastics from algae [3]. Figure 1 shows the comparison between conventionally manufactured bioplastics with microalgae-based bioplastics.

The review paper begins by outlining the various natural resources that are used to create bioplastics. This includes corn starch, wheat starch, and sugarcane bagasse. Additionally, the production of bioplastics uses a variety of sources. We then discuss microalgae as a potential source of bioplastics after discussing these sources.

It is regarded as one of the most promising sources of bioplastics production due to its sustainability, carbon capture, minimal land use, high biomass yield, variety of strains, versatility, waste utilization, biodegradability, reduced energy

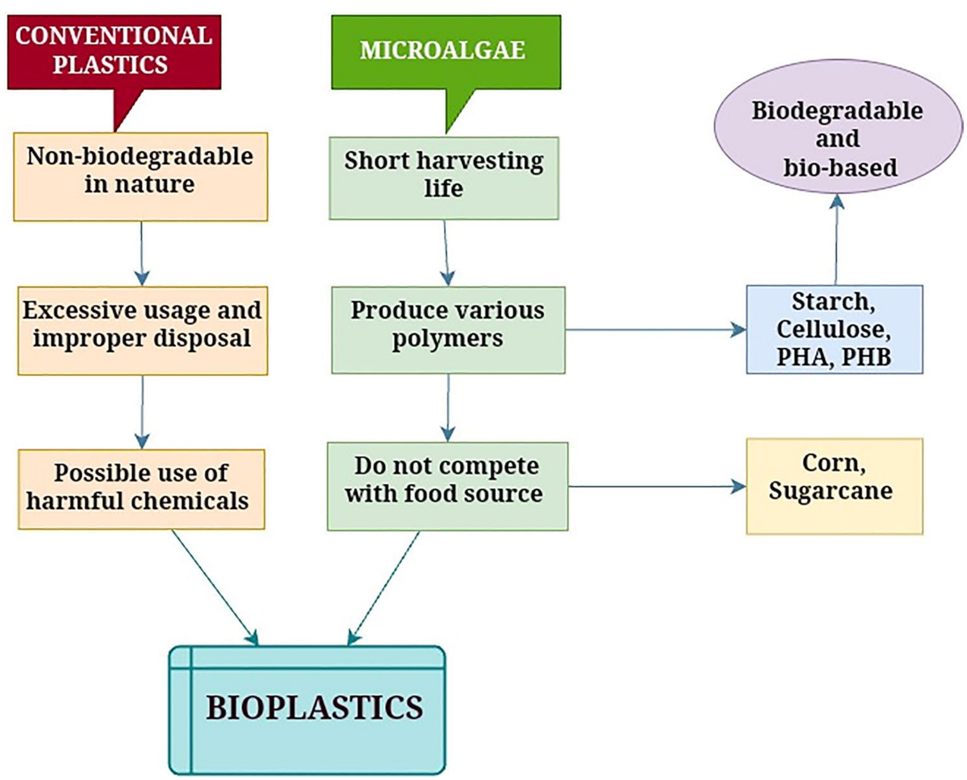


Fig. 1 The comparison between conventional bioplastics and microalgae-based bioplastics. According to the data, using conventional methods to make bioplastics will cause significant problems like non-degradability and the usage of hazardous chemicals during its production. However, using microalgae as a source for making bioplastics offers numerous benefits, like having a quick harvesting time, not competing with food supplies, and having the ability to make various kinds of biopolymers. [17]

consumption, circular economy, reduced food competition, and many other factors. The characteristics of various microalgal species for making bioplastics are then mentioned. *Spirulina* species and *Chlorella* species are two of these that are useful for making bioplastics.

We discuss the biopolymers found in microalgae, such as PHA and PHB. In the production of microalgae-based bioplastics, polyhydroxyalkanoates (PHAs) and polyhydroxybutyrate (PHB) are two significant classes of biodegradable polymers. PHAs are suitable for a variety of applications, including packaging, agriculture, and medical devices, because they have characteristics similar to those of conventional plastics [4]. They provide an environmentally friendly substitute for plastics made from petroleum because they are biocompatible and degradable. PHB is one of the most well-known biodegradable plastics and a particular kind of PHA. It can be composted and degrades naturally, lessening its impact on the environment. The production process of bioplastics is discussed in the next section. Usually, the production process includes methods such as microalgae selection, cultivation, harvesting, lipid extraction, and bioplastic synthesis. These are the major stages of producing bioplastics from microalgae. Then, the mechanical properties, such as tensile strength and elongation, of the produced bioplastics are discussed. Ensile strength measures the ability of a material to withstand a stretching force without breaking. Bioplastics made from microalgae can have varying tensile strengths depending on factors such as the microalgae strain used, the polymerization process, and any additives included in the formulation. Elongation at break represents the extent to which a bioplastic can stretch before breaking. It is a critical property for flexible applications such as packaging materials. Depending on their composition and processing, microalgae-derived bioplastics can have a range of elongation capabilities. The next step is to conduct a thermal analysis of bioplastics. Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) were used in this procedure [5]. The thermal degradation and decomposition of microalgae-based bioplastics were analyzed using TGA. It reveals the temperature at which weight loss takes place and the degree of decomposition. TGA provides information on variables such as residue (the mass that remains after decomposition), peak temperature (the temperature at which the maximum rate of degradation occurs), and onset temperature (the temperature at which degradation begins). Understanding these variables is essential if one is to comprehend the thermal behavior of bioplastics. The thermal characteristics and transitions of microalgae-based bioplastics are investigated using DSC, which offers details on variables such as Tg (the temperature at which the material changes from a glassy to a rubbery state), melting enthalpy (the heat required for melting), and crystallization enthalpy (the heat released during crystallization). Following that, we go over a few additional analytical techniques, including SEM (scanning electron microscopy) and FTIR (Fourier transform infrared spectroscopy). Microalgae-based bioplastics can be visually inspected using a scanning electron microscope (SEM), while their molecular structure and chemical makeup can be precisely determined using FTIR spectroscopy. These methods work together to provide a thorough understanding of the qualities and characteristics of bioplastics made from microalgae. The economic viability of microalgae-based bioplastics is discussed. A thorough economic analysis of the production of microalgae-based bioplastics should be taken into consideration to provide a clear understanding of the economic viability and potential difficulties connected with this ground-breaking and environmentally friendly method of producing bioplastics. The paper also covers the shelf life and biodegradability of microalgae-based bioplastics. Additionally, it highlights the various uses and restrictions of microalgae-based bioplastics.

This review paper summarizes the current state of knowledge on microalgae-based bioplastics in its conclusion, highlighting their importance in reducing environmental problems associated with plastic use. This review advances our knowledge of microalgae-based bioplastics in the quest for a more sustainable plastics industry by offering a fair evaluation of their advantages, disadvantages, and potential applications.

2 Various sources for the production of bioplastics

Bioplastics, the innovative materials of the modern era, are laying the foundation for sustainable and environmentally friendly alternatives to conventional plastics. Bioplastics holds the promise of reducing our reliance on fossil fuels and the environmental impact of plastic waste because they are made from a variety of renewable sources, such as plants, microorganisms, and agricultural waste. The various resources used to produce bioplastics are covered in this section.

2.1 Corn starch

Plastics made from biofibers are favored because of their affordability, sustainability, and mechanical qualities. Corn husks are one type of agricultural waste that has a significant impact on the environment. Utilizing these wastes for the creation of bioplastics could aid in lowering environmental pollution and promoting the use of eco-friendly plastics. Plastics made from maize husks, Corn Husk Plastics (CHP) have a high Young's modulus, good transparency, and tensile strength. The procedure is also quick, efficient, and environmentally friendly. [6].

When used as a filler, maize starch exhibits great mechanical qualities, such as a high elasticity modulus, a porous structure, and chemical reactivity. The quality of bioplastics is impacted by the storage temperature. The linkages between the filler, starch, and glycerol will not deteriorate if they are stored at a low temperature. The bioplastic exhibits no damage, holes, tears, or wrinkles while stored at various temperatures, according to Scanning Electron Microscopy (SEM) observations of the material [7].

It will take longer for the bioplastics made from corn starch to slurry up or thicken. Additionally, the decreased amylose content in maize starch makes it challenging to produce a gel quickly. The hardened corn-based bioplastic will become much thicker and sticky after numerous uses. [8].

2.2 Sugarcane bagasse

After the sugarcane is crushed and the juice is extracted, lignocellulosic waste known as sugarcane bagasse is produced. Sugarcane bagasse's cell wall is made up of cellulose, 28.6% hemicellulose, 23.5% lignin, 1.3% ash, and 2.8% miscellaneous substances. The concentration of cellulose makes it more suitable for the production of bioplastics. The lignin, hemicellulose, and other components of sugarcane bagasse will be removed during the alkaline treatment, increasing the amount of cellulose that is available. Lignin and hemicellulose are not present in the bagasse following the alkali treatment, according to a Fourier-transform spectroscopy (FTIR) examination. This alkali-treated sugarcane bagasse is a filler for bioplastics made from starch. The tensile and mechanical properties of bioplastics are improved by the addition of sugarcane bagasse to starch-based materials. [9].

The mechanical and tensile strengths of cellulose acetate-based bioplastics are good. Additionally, it offers qualities such as high transparency, biodegradability, ease of solubility in nonpolar solvents, and natural nontoxicity. Because it has poor economic value, cellulose is typically extracted from industrial waste. Bagasse made from sugarcane contains a large amount of cellulose. As a result, sugarcane cellulose is extracted and then acetylated to produce cellulose acetate. After that, sorbitol is added as a plasticizer, and chitosan is added as a bio filler. Bioplastics made of cellulose acetate are fragile by nature. Chitosan can be added to it to improve tensile strength while reducing brittleness. The addition of sorbitol to this combination can improve the way polymers absorb water and elongate. Additionally, the degradation period is shortened to 12 days from 24 days [10].

2.3 Wheat starch

Bioplastics are produced from wheat due to its high starch content. The plasticizers glycerol, sorbitol, fructose, and urea are added to the biodegradable films to increase their flexibility. The flexibility and range of motion of bioplastics will be improved by these plasticizers. The bioplastic films' ability to elongate significantly increases when 35% sorbitol is added. The film's tensile strength is increased by adding 35% more fructose. The plastic elongates more because of the 15% increase in urea used as a plasticizer. Plasticizers are added to increase water resistance. The film's morphological perspective reveals a uniform surface. According to this investigation, a 35% increase in the fructose concentration as a plasticizer can be the best choice for producing bioplastics with improved characteristics [11].

When sugar palm fiber was used as reinforcement, the characteristics of wheat starch PVA bioplastic were improved. The two types of fibers are combined: treated and untreated fibers. The untreated fiber exhibits a bioplastic that is lighter and less dense. The density of the coating is further reduced in the treated fibers. The inclusion of fibers improves the thermal stability and crystal profile. Only 9% of the treated fiber enhanced the tensile strength and elongation of the film, indicating that the increase in mechanical properties was not uniform. When compared to untreated fibers, the inclusion of treated fibers demonstrates higher mechanical qualities. [12].

2.4 Microalgae: a potential source for producing bioplastics

Even if there are several natural resources for making bioplastics, many of these sources will contribute to the food crisis, which is a great issue. The food economy can suffer because of the manufacture of bioplastics from these sources. As a result, microalgae have emerged as a promising source for making bioplastics. Due to their ease of development, minimal feed and growth environment requirements, and ability to grow quickly, these microalgae are best suited to produce bioplastics. In addition, compared to materials from other sources, bioplastics offer excellent mechanical and tensile strength. The production of bioplastics involves the intracellular synthesis of microalgal biopolymers such Polyhydroxy alkanoate (PHA) and Polyhydroxy butyrate (PHB) [13]. Microalgae are one of the most promising sources for making bioplastics because of their quick growth and simple synthesis with excellent characteristics.

3 Bioplastics from various microalgae species

There are many distinct species of microalgae in the world, each with their own special qualities and the potential to produce bioplastics. We set out on a fascinating journey through the fascinating world of microalgal species used in the production of bioplastics in this brief introduction. These tiny aquatic organisms, which include Chlorella, Spirulina, and others, are the key to developing sustainable, biodegradable materials that have the potential to completely transform the plastics industry. In this section, we explore the variety of microalgal species, their individual contributions to bioplastics, and the bright future they hold in the search for environmentally friendly materials. In Table 2, various microalgae strains used for bioplastics production are listed with its culture conditions, biopolymers present in it and the yield of bioplastics.

3.1 Spirulina sp.

Without the need for binders or solvents, bioplastics are effectively produced using *Spirulina sp*. When compared to plastics made from petroleum, such as polystyrene, the created bioplastic has superior tensile qualities. *Spirulina*-based polymers have excellent tensile strength, elongation, and flexibility [14]. *Spirulina* species can synthesize biopolymers such as PHA and PHB under photoautotrophic conditions. In bioplastic composites, it can also be utilized as a filler or a reinforcing fiber. The mechanical qualities of generated bioplastics can be improved by using microalgae-filled biocomposites [15].

3.2 *Chlorella sp*.

One of the possible sources to produce bioplastic is *Chlorella sp*. The bioplastic made from *Chlorella* often has low melting points. By incorporating a compatibilizer into the plastic, the melting point can be enhanced. The tensile strength and mechanical properties of the *Chlorella*-PVA bioplastic are improved through the pretreatment procedure of an ultrasonic homogenizer. To improve the mechanical qualities of PVC, *Chlorella* is added as a filler [15]. Comparing *Chlorella* biomass

Table 2 Various strains of microalgae used in bioplastics production

Strain	Culture conditions	Biopolymers	Yield %
Nostocmuscorum	Acetate in medium + Dark incubation	PHB	43
Synechococcus sp. MA19	Autotrophy, Phosphate deprivation	PHB	55
Synechocystis sp. PCC6803	Glucose containing BG11(Pre grown) medium + Acetate + Phosphhate deprivation	PHB	29
Synechococcussubsalsus	Nitrogen deprivation	PHA	16
Spirulina sp.	LEB-18 Nitrogen deprivation	PHA	12
Spirulina subsalsa	Increased salinity + Nitrogen deprivation	PHA	7.45
Calothrixscytonemicola	Photoautotrophy in nitrogen limitation	PHB	25.4 ± 3.5
Aulosirafertilissima	Acetate and citrate supplemented medium	PHB	66
Aulosirafertilissima	Acetate supplementation + Phosphate deprivation	PHB	77
Anabaena cylindrica	Acetate supplemented BG11 medium	PHB	2
Spirulina maxima	Acetate supplemented Mixotrophic conditions	PHB	3
Microalgal consortium	Waste water	PHA	43

to cellulose-based polymers, *Chlorella* biomass disintegrates more easily. Added as a sorbent for the manufacture of bioplastic is fungal Mycelium. *Chlorella* sp. utilization is an economical and long-lasting strategy [16].

4 Bio-polymers from microalgae

4.1 Polyhydroxyalkanoates (PHAs)

The most often utilized natural polymer in the production of bioplastics is polyhydroxyalkanoates (PHAs). By enzymatic action, it may be broken down [17]. It has extremely high production costs. It can be obtained from a variety of microorganisms, including Cyanobacteria and Chemoautotrophic bacteria [18]. With the aid of acetyl coenzyme A, microalgae are able to manufacture PHA when they are grown in nutrient-poor circumstances [19]. PHA bioplastics are an effective replacement for commercial plastics due to their biodegradability and lack of toxins. PHA is manufactured on a small scale, and as it must be extracted from microbes, it is expensive and not accessible to people. However, it is advised due to its inability to dissolve in water as well as its resistance to UV and O_2 permeability. When compared to conventional plastics, PHA bioplastics also exhibit good mechanical qualities.

4.2 Polyhydroxybutyrate (PHB)

In several applications, a form of PHA called Polyhydroxy Butyrate (PHB) is employed as a biopolymer [18]. It is an effective O_2 barrier. PHB is mostly utilized in the form of nanocomplex tubes and films, which are then packaged with fertilizers and insecticides. Bone plates, surgical sutures, and other medical applications also utilize PHB. PHB is transformed into Crotonic acid when it is treated with Chloroform [1].

Chlorella pyrenoidosa was introduced to Fogg's medium along with water, HCL, and chloroform to examine its PHB concentration. It is then added to concentrated H_2SO_4 to create crotonic acid. The UV absorbance peak was then measured using a spectrophotometer at 230 nm absorbance and was found to be 0.08. The PHB level of algae affects how biodegradable they are [20]. Figure 2 also visually depicts the PHB content in the various microbial biomasses. The PHB concentrations are expressed as milligrams of microbial biomass per milliliter. The information depicts the average values discovered from numerous measurements for each microbial species. The data show that *Chroococcus turgidus* has a low PHB content while Microcystis sp. from High-rate algal ponds (HRAP) has a high PHB concentration [1].

5 Production process of bioplastics involving microalgae

Microalgae-based bioplastics are produced through a challenging but fascinating process that uses the strength of these microorganisms to produce sustainable materials. Typically, the process of making microalgae-based bioplastics involves several steps, including microalgae selection, cultivation, harvesting, lipid extraction, bioplastic synthesis,

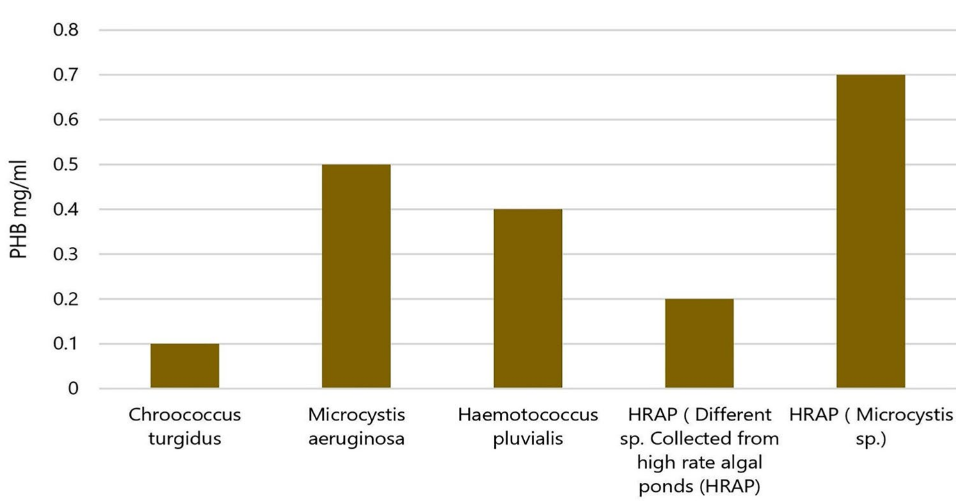


Fig. 2 PHB concentration in different microbial biomasses [1]. The PHB concentrations are expressed as milligrams of microbial biomass per milliliter. The information depicts the average values discovered from numerous measurements for each microbial species. The data show that *Chroococcus turgidus* has a low PHB content while Microcystis sp. from HRAP has a high PHB concentration. *HRAP* High-rate algal ponds

characterization, and waste utilization. The journey starts with the thoughtful selection of microalgae strains, which are recognized for having prominent levels of lipid and biomass. The main source of bioplastic precursors comes from these strains. Microalgae are grown in specialized bioreactors or ponds with growth-promoting environmental conditions. To ensure maximum biomass production, variables such as light intensity, temperature, and nutrient levels are carefully regulated. The microalgae are harvested once they have reached the desired biomass. The microalgae are separated from the growth medium using a few techniques, such as centrifugation, filtration, and flocculation. Lipid extraction is the process used to separate and purify valuable lipids from harvested microalgae. The building blocks for the synthesis of bioplastics are these lipids. The lipids are then converted into bioplastics using a variety of polymerization processes. These lipids are used to create a common class of biodegradable polymers known as polyhydroxyalkanoates (PHAs). To ensure quality and suitability for applications, the resulting bioplastics are rigorously characterized, with an assessment of their molecular weight, thermal properties, and mechanical properties. Waste streams and byproducts are minimized and reused throughout the production process. These can include minimizing waste and maximizing resource utilization, as well as residual biomass to produce biofuels or other high-value compounds.

Abiotic and biotic variables, culture medium (pH, nutrients, light, salinity, temperature), uneven distribution of sunlight in culture media, etc., are the factors that affect the growth of microalgae [19]. You can produce microalgae in either open or closed systems. An open system is a simple and affordable solution. However, the product has an extremely high level of contamination and little manufacturing. Photobioreactors are utilized for closed systems. However, it is an expensive method for high production [17]. Other closed systems include bubble columns, airlifts, and flat-plane reactors [18].

A film formulation that contains 7% solid film-forming suspension is taken. The cassava starch content of the suspension was 4%, the glycerol content was 1%, and the cassava bagasse, gelatin, and *Spirulina platensis* content was 2%. Following that, the suspension is homogenized by constant stirring. The mixture was then heated to produce a fully homogenized solution. It is heated and then transferred to a mold made out of a square piece of acrylic. It is given time to dry. Once they have cured, the bioplastics are demolded. [21].

Bioplastics can be made by adding fillers and compatibilizers. A combination of substances, including maleic anhydrides, PVA, dimethyl sulfate, and potassium peroxydisulfate, make up the compatibilizer in this case. Glycerol, distilled water, and the microalga Spirulina platensis are the ingredients in the filler. The compatibilizer and filler liquids are combined and then poured into a glass mold. After that, the mold is heated and given time to cool. The bioplastics are demolded and put to use once they reach room temperature. [22].

Thermoplastic *Chlorella* and polyvinyl alcohol-g-maleic anhydrides can also be combined to create bioplastics. These two elements were combined and then poured into a glass mold. It is cooked for a while after being filled into the mold and then allowed to cool. The glass molds are removed, and the bioplastics are obtained after cooling. [23].

Bioplastics are created by combining *Chlorella* solutions and polyvinyl alcohol (PVA). The PVA solution and *Chlorella* solution are made separately for this method. When combined, PVA and distilled water are heated to 800 °C. *Chlorella* is then combined with glycerol at a temperature of 900 °C to create the following solution. Citric acid is additionally included in the PVA solution. Both solutions have now been combined. It is then poured onto a glass plate and left to cure at room temperature. The bioplastic is taken from the glass plate after drying [24].

6 Mechanical properties

6.1 Tensile strength

Tensile strength is one of the key features of bioplastics. As the percentage of algae biomass in the PLA blend rises, the tensile strength will drop. This is a result of the algae and PLA's attachment to one another. The tensile strength of bioplastics can be increased by adding Epoxidized Soybean Oil (EPO) to plastic [6]. The tensile strength and other mechanical properties of bioplastics can also be enhanced by adding more protein. We can use the following formula to determine the tensile strength of the bioplastic [21].

$$\text{TENSILE STRENGTH} = F\max / A\min$$

whereFmax = Maximum force (N)Amin = Minimum initial samples used (mm^2)

The bioplastic tensile strength is increased by the compatibilizer concentration. The 6% increase in compatibilizer will significantly boost the tensile strength. Commercial plastic bags have a tensile strength of 26.37 kg/cm^2, but bioplastic bags have a tensile strength of 28.26 kg/cm^2 when 6% compatibilizer is added [25]. The tensile strengths of commercial plastic and bioplastics made from microalgae were determined to be 1.35 MPa and 1.62 MPa, respectively [1]. The tensile strength of the bioplastics is inversely correlated with the plasticizer concentration. The tensile strength gradually declines as the glycerol content rises. Bioplastics have a better tensile strength than industrial plastics [22].

6.2 Elongation

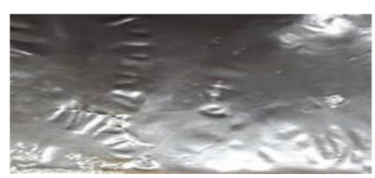
The elongation is observed to increase when plastic is combined with *Spirulina* [6]. An equation is employed to calculate the maximum elongation breaks [21].

$$\text{ELONGATION BREAK} = \text{Ar}/\text{Dg}$$

whereA_r = Elongation at break (mm^2).DG = Initial distance between the grip (mm).

The bioplastic elongation is inversely correlated with the compatibilizer content. The bioplastic elongation is significantly boosted when the maleic anhydrous (Compatibilizer) concentration is raised by 6% [25]. Commercial plastics have an elongation of 307%, while bioplastics have an elongation of 530%, according to a comparison of their elongations [1]. The percentage of elongation is related to the plasticizer concentration. The elongation can rise by as much as 66% with the addition of 1.2 ml of glycerol. Commercial plastics have more elongation than bioplastics, according to a comparison between them and the bioplastics that have glycerol added. Commercial plastics exhibit higher elongation than bioplastics, according to a comparison of the two materials with glycerol added. Because of this, bioplastics cannot be employed for commercial or industrial applications. It can be applied to the packaging

Table 3 The appearance of films when various compatibilizer (Maleic Anhydride) concentrations were added [23]

Compatibilizer concentration	Appearance of film	Images
0%	Rough, brittle, fragile, many pores, less flexible, difficult to peel	
2%	Less pores, more flexible, less rough than without, difficult to peel	
4%	Less pores than M2, slightly elastic, easy to peel	
6%	No pores, more flexible, more elastic, easy to peel	

The film's visual appearance after PVA/Chlorella blending with various compatibilizer concentrations is described in the table. Accordingly, when compared to other concentrations, the 6% compatibilizer concentration can result in better films. This 6% concentration can produce films that are more flexible, have fewer or no pores, and are simple to peel of foods, cosmetics, and other goods [22]. Table 3 provides a summary of a film's appearance based on various compatibilizer concentrations.

7 Thermal analysis

7.1 Thermogravimetric analysis (TGA)

The one-step degradation peak of a bioplastic for an algal biomass community is discovered to be at 295 °C, and the weight loss owing to water loss is discovered to be at 115 °C. As a result, it was determined that 86.9% of the entire weight had been lost, leaving 13.1% of the loss of inorganics. Similarly, the *Spirulina* blend's two-step degradation peak is at 317 °C, while the weight loss from water loss is at 91 °C. In this case, there was a 94.8% overall weight loss and a 5.2% loss of residual inorganics [6]. This demonstrates that the *Spirulina* mix has greater thermal resistance against deterioration than the algal biomass.

The TGA of bioplastics is examined using two distinct biomasses. Microalgae Consortium and *Arthrospira* biomass are the two types of biomasses. Both biomasses exhibit weight reduction in three distinct phases. Water loss causes weight loss in the first stage, which peaks at approximately 750 °C. The degradation of lipids, proteins, and carbohydrate molecules in the biomass occurs in the second stage at a temperature range of 200 to 490 °C. Solid residues are broken down in the third step at temperatures between 200 and 490 °C. This results in a weight loss of 70% for both types of biomasses. [26].

7.2 DIfferential scanning calorimetry (DSC)

The changes held in the plastic as a result of temperature are verified using the glass-transition temperature (T_g) and melting temperature (T_m). The analysis utilizing Differential Scanning Calorimetry (DSC) was conducted using polylactic acid (PLA) and the algal biomass of Spirulina. The samples were prepared and cooked in a nitrogen environment for analysis. According to this, the glass transition temperature (T_g) for PLA is 76.8 °C, while the Tg for algal biomass is 72.2 °C–74.3 °C. The temperature at which PLA melts is 153.3 °C. [6].

Heat 2 mg of PHAs in an aluminum pan between 250 and 6000 °C. Liquid nitrogen is utilized as a coolant, and helium gas is used as a pure gas in the cooling process. The melting point of PHA has now been determined to be 1700 °C. *Synechococcus subsalsus* has a crystallinity of 37.09%, while Spirulina sp. has a crystallinity of 45.15%. The PHA from *Synechococcus subsalsus* can be employed in industrial settings, mostly for packing, due to its low crystallinity. [27].

The T_g of microalgae starch is 1.8 °C, which is higher than the T_g of pure starch or the glycerol system. Since the temperature attained after heating is 1.6 °C, the second heating of the algal biomass at 150 °C does not significantly alter the temperature at which glass transitions occur [28].

8 Analytical methods

8.1 Scanning electron microscope (SEM)

A scanning electron microscope (SEM) is used to examine the surface of a solid sample. To increase the conductivity of the sample surface, a sample is obtained and either sputtered with gold or coated with it. Then, for a closer look at the surface, it is conducted at various magnification levels, such as 500 times, 1000 times, and 2000 times. We can identify the mechanical characteristics, such as tensile strength, elongation, and flexibility, using SEM and compare them to those of commercial plastic. [25].

A biological sample's particle size, shape, and distribution can also be estimated using SEM. SEM analyses of the sample reveal that when combined with other substances, particles smaller than 50 mm have a better distribution in the medium. This improves its suitability for making bioplastics. [1].

Chlorella that has been ultrasonically pretreated has been discovered to have a homogenized structure, few pores, and a smooth surface. This leads to the discovery that ultrasonication enhances PHA and *Chlorella* binding to create homogenized bioplastics. [24].

Under SEM, PVA-g-maleic anhydrous or *Chlorella* biomass was examined. For this, the tensile and liquid nitrogen-frozen fractured surfaces of the composites were collected and dried. Following that, it is gold-sputtered before going into the SEM. The samples are examined at 500X and 6000X magnification levels. The sample without the compatibilizer is examined, and it is discovered to have an uneven surface, many pores and granules, and some contaminants. When analyzed with 6% compatibilizer, it is found to have a smooth film, dense film structure, no cracks or pores, and a homogenized surface. [23].

8.2 Fourier transform infrared spectroscopy (FTIR)

The analytical method known as Fourier transform infrared spectroscopy (FTIR) is employed. The presence of a hydroxy group, which renders the film soluble in water, is indicated by the peak at 3650–3200 cm^{-1}. The presence of a C–H bond, or a hydrogen bond between amylose and amylopectin in *Chlorella*, is shown by the peak at 2200–1800 cm^{-1}. The presence of protein in *Chlorella* that was partially bonded with PVA is indicated by the peak at 1600–1320 cm^{-1}. The ether group (C–O) and acetyl ring (C–O–C), which are the bonds of PVA and *Chlorella*, are indicated by the peak between 1320 and 1140 cm^{-1}. [24].

A PHA sample was analyzed by FTIR at magnifications between 4000 cm^{-1} and 6000 cm^{-1}. The peaks between 1710–1750 cm^{-1} indicate the deformation of carbonyl groups (C = O). At the peaks between 1260 and 1300 cm^{-1}, the formation of the C–O–C group is found. The peak at 1380 cm^{-1} corresponds to the deformation of the methyl group.

9 Economic analysis

The economic analysis of large-scale microalgae farming as a sustainable and cost-effective source for manufacturing bioplastics explores a variety of crucial factors, presenting a thorough comparison with conventional petroleum-based plastics. The examination encompasses production costs, income possibilities, and return on investment (ROI), providing insights into the economic sustainability of this innovative approach to bioplastic production. In contrast to traditional petroleum-based plastics, microalgae-based bioplastics are scrutinized for their production costs, considering raw material expenses, labor, energy, and equipment. This comparative analysis aims to shed light on the economic viability of transitioning from conventional plastics to a more sustainable alternative. The study delves into potential revenue streams from microalgae-based bioplastics, offering a comparative lens for income possibilities against the backdrop of petroleum-based counterparts. Furthermore, the ROI is meticulously assessed, weighing the initial capital outlay against the projected earnings, thereby providing a holistic view of the economic prospects associated with large-scale microalgae farming [29].

Crucial factors influencing the commercial viability of microalgae-based bioplastics are then explored. Biomass output is examined for its impact on production costs and overall profitability, with a focus on strategies to optimize production efficiency. The evaluation of various growing techniques emphasizes cost-effectiveness and scalability, encouraging the adoption of innovative methods to enhance productivity and reduce operational costs [30]. Additionally, market dynamics are considered to anticipate shifts in demand and adapt production strategies accordingly, underlining the importance of staying attuned to industry trends.

A specific economic evaluation of bioplastics employing the cyanobacterial PHB biopolymer is presented in Table 4, offering a detailed breakdown of capital costs, operating costs, and labor savings. This section provides a more granular understanding of the economic landscape associated with microalgae-based bioplastics, facilitating informed decision-making in the pursuit of sustainable alternatives. The cost breakdown, visualized in Fig. 3, elucidates the distribution of capital expenditure and operating costs throughout the bioplastic production process. Microalgae cultivation emerges as a significant contributor to operating costs, emphasizing its pivotal role in determining economic feasibility.

Table 4 Estimation of the production costs of PHB from cyanobacteria [29]

		Description	Assumption	Price
Fixed Capital investment	Direct Costs (DC)	Major equipment costs (MEC)		
		Cultivation	–	–
		Concrete	–	3094 €
		Steel (reinforcement)	–	997 €
		Steel (plate)	–	5027 €
		Polymethyl methacrylate (reactors)	–	41,880 €
		Harvesting	–	–
		Centrifuge	–	6205 €
		PHB Extraction	–	–
		Mixing tank 1	–	3000 €
		Decanter Centrifuge	–	25,000 €
		Evaporator	–	49,900 €
		Mixing tank 2	–	3000 €
		Centrifuge	–	18,500 €
		Evaporator	–	950 €
		Installation costs	47% MEC	74,050 €
		Instrumentation and control	35% MEC	55,144 €
	Indirect cost (IC)	Construction expenses	15% MEC	23,633 €
		Engineering and Supervision	10% DC	28,675 €
	Other cost	Contractor's fee and contingency costs	20% (DC + IC)	67,811 €

Table 4 (continued)

		Description	Assumption	Price
OPEX (Operating expense/expenditure)	Electricity[1]	–	Calculated from equipment consumption and average electricity costs in 2021 in Spain for household consumers	0.1647 € kwh^{-1}
	Labor	–	–	9912.7 € $year^{-1}$
	Operator	–	Salary of 1 worker (20% of standard workweek hours)	6000 € $year^{-1}$
	Supervisor	–	Salary of 1 worker (20% of standard workweek hours)	800 € $year^{-1}$
	Plant manager	–	Salary of 1 worker (20% of standard workweek hours)	1300 € $year^{-1}$
	Employer's contribution	–	23.6% of the labor costs	1892.7 € $year^{-1}$
	Maintenance	–	4% MEC	6302 € $year^{-1}$
		–		
	Chemicals	–	Calculated from mass balances	
	Cultivation	–	–	
	CO_2	–	–	
	$NaNO_3$	–	Only considered in scenarios using standard Bluegreen algae growth medium BG-11	29.8 € kg^{-1}
	$MgSO_4.7H_2O$	–	–	45€ kg^{-1}
	Citric acid	–	–	54 € kg^{-1}
	K_2HPO_4	–	–	80.7 € kg^{-1}
	Ammonium ferric citrate green	–	–	36 € kg^{-1}
	CaCl $2H_2O$	–	–	42.1 € kg^{-1}
	EDTA Na_2	–	–	120 € kg^{-1}
	$NaCO_3$	–	–	23 € kg^{-1}
	PHB extraction	–	–	
	Water	–	–	2.7 € kg^{-1}
	NaClO	–	–	0.6 € kg^{-1}
	Chloroform	–	–	41.8 € kg^{-1}
	Methanol	–	–	7.9 € kg^{-1}

For all scenarios, the system had a total capital expenditure of 406,868 €. The major equipment (157,554 €, or 39% of the total capital investment expenses) was the most expensive component of the systems. The photobioreactors ($50,999; 13% of total capital investment costs) and evaporator ($49,900; 12% of total capital investment costs) were the pieces of equipment with the higher costs. The categories that contributed the most to the capital costs, after major equipment, were installation (74,050 €, 18% of the total capital investment costs), and instrumentation (55,144 €, 14% of the total capital investment costs). In terms of operating and maintenance costs, labor and maintenance expenditures represented the largest operational costs in each scenario (26% and 16% of the overall operational and maintenance costs, respectively)

[1]The power costs considered here will grow by 57% in 2022, from 0.1647 euros per kilowatt-hour in 2021 to 0.2579 euros per kilowatt-hour in the first semester

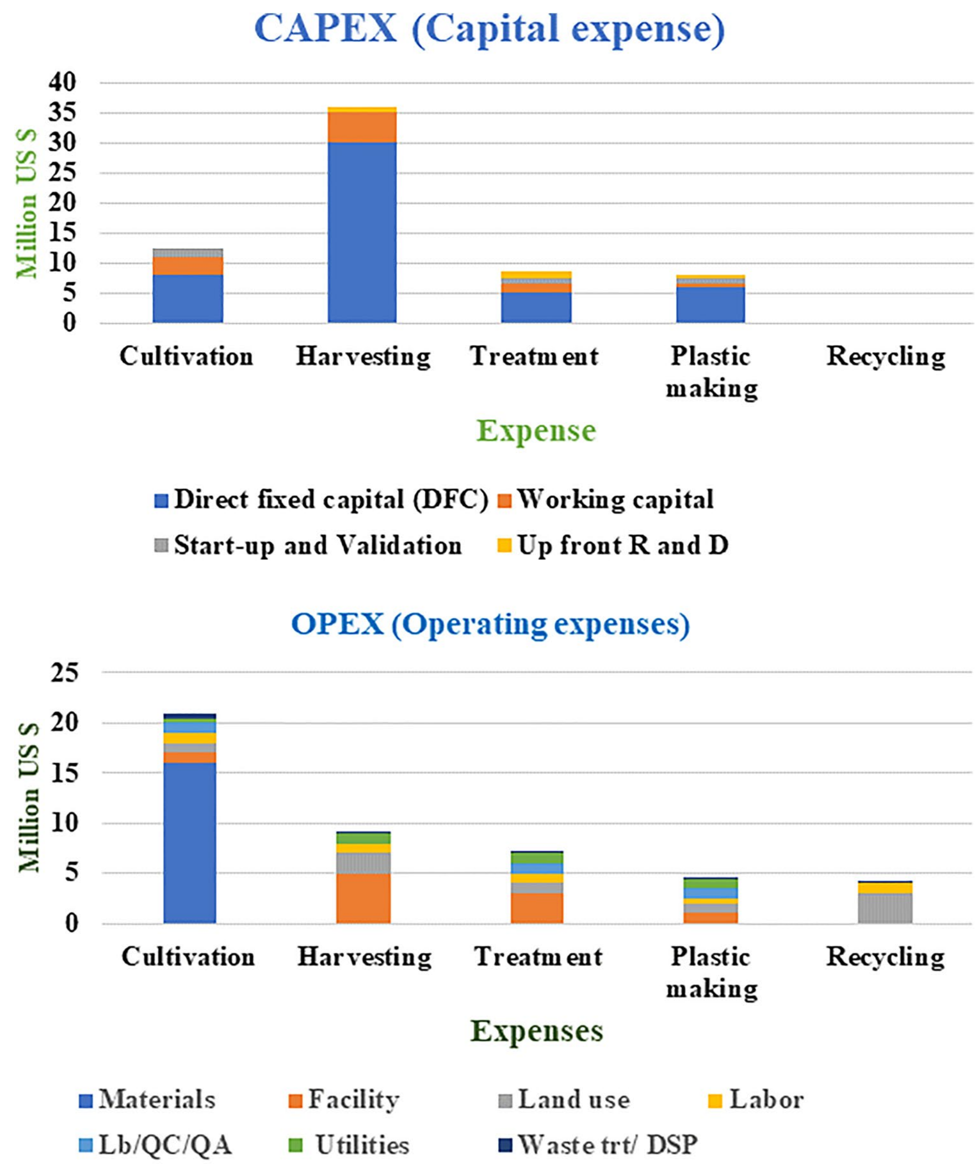


Fig. 3 Results of the economic cost: **a** CAPEX and **b** OPEX of the Spirulina biorefinery. [30]. The primary capital expenditure is made for the microalgae species harvesting, followed by the cost of its growing and, in addition, a small amount for the processes involved in its treatment and production. Microalgae cultivation makes up the majority of the operating costs, which are then moderately covered by harvesting, processing, and manufacturing costs. *CAPEX* CAPITAL EXPENSE, *OPEX* OPERATING EXPENSE

10 Biodegradability

Not all biobased polymers can be broken down by nature. For instance, while polymers such as Polyethylene (PE), Polyethylene terephthalate (PET), and Polyethylene furanoate (PEF) are made from sustainable and renewable resources, they cannot be broken down. This is because biodegradability is influenced by the chemical makeup of plastics, such as crystallinity, and external elements, such as pH, temperature, moisture, etc. It takes PLA, a bioplastic, 10 years to decompose, which is a sluggish rate for a bioplastic. PHA is easily biodegradable in any circumstance. The properties of biopolymers and the environment play a significant role in how quickly they degrade [31]. Short chain, poor crystallinity, and low formulation polymers degrade quickly. The most common commercial applications for starch-based polymers include film, foam, injection molding, and edible coatings for food goods. However, it has shortcomings such as hydrophilicity and brittleness, which can be remedied by certain starch modifications. To increase its durability, plasticizers and compatibilizers have been added. To increase the mechanical strength of bioplastics, starch can be mixed with other polymers, such as Polyvinyl alcohol (PVA), PLA, and PE. Highly biodegradable bioplastics such as starch and cellulose-based polymers can be utilized for food with a limited shelf life. Similarly, low-biodegradability plastics such as PHA and PLA can be utilized for foods with a long shelf life [32]. Most bioplastics are biodegradable, and when they do so, they breakdown into carbon dioxide and water. Bacteria, fungi, and other microorganisms excrete enzymes that hydrolyze solid PHA into water-soluble monomers and oligomers.

A plastic's tendency to biodegrade is mostly determined by its chemical composition, not by the source from which the monomer was obtained [17]. The main causes of the biodegradation of bioplastics are fouling, corrosion, hydrolysis, penetration, and degradation [2]. The lifespan of plastic can be increased, and its mechanical qualities can be enhanced by blending bioplastics with polymers, starches, and other natural materials, such as cellulose and starch [17].

11 Shelf-life of bioplastics

The main benefit of plastic is that it prevents the goods from deteriorating and staying fresh inside. Commercial polymers made of petroleum can be found with ease that have this shelf-life feature. However, this is difficult to achieve with bioplastics and can be done by adding certain molecules. The two main elements that affect the shelf life of goods containing bioplastics are oxygen and humidity. In bioplastics, a starch layer is coated to lengthen the shelf lives of food products. Additionally, this coating layer offers a strong defense against harmful substances and other elements that might taint food. Active packaging refers to the method of combining the packing material with antimicrobials and antioxidants to increase shelf life. To increase the polymers' shelf-life qualities, these antimicrobials and antioxidants are directly added to them [31]. To extend the shelf life of tomatoes, PLA is combined with halloysite nanotubes. Materials utilized in active packaging include chitin and chitosan. The shelf life of cosmetics is extended when selenium chitin is used in their packaging [32]. By preserving them, starch-based polymers primarily aid in extending the shelf life of fruits and vegetables [33].

12 Advantages of natural bioplastics

1. Bioplastics are used as a substitute for traditional plastics, which are harmful.
2. The use of bioplastics in the food industry is one of the most essential practices for reducing the pollution caused by the disposable use of nondegradable commercial plastics.
3. As they are produced from natural, renewable resources, they can reduce CO_2.
4. In the medical field, bioplastics have immense applications, such as in postsurgical ulcer therapy, wound healing dressings, cancer detection, heart valves, artificial blood vessels, and bone tissue engineering [3].
5. They are influenced by their day-to-day use of products such as bottles, cans, plates, glasses, bags, and covers. These biodegradable forms of plastic can degrade naturally, causing no impact on the environment [6].
6. Biodegradable polymers are used as promising sources in drug delivery systems because of their superior performance and safety [31].
7. PHA bioplastics is effectively used as a drug delivery system in cancer treatment [31].
8. Biopolymers such as PHA, Polybutylene succinate (PBS), Poly D,L-lactic acid (PDLLA), Polylactic-co-glycolic acid (PLGA), and Poly-l-lactic acid (PLLA) have been used in tissue engineering [31].
9. PLA is widely used in 3D printing technology due to its low melting point, which makes use of less energy and saves cost and energy [31].
10. Nanocellulose bioplastics are used in the food industry for packing foods due to their edibility, flexibility, biodegradability, and antimicrobial properties, which make the packaging extremely attractive and keep the food fresh [32].
11. Cosmetic products have excellent value in society. However, they can be easily damaged while transporting or during any other activity. Currently, the use of bioplastics is mostly preferred due to their biodegradability and sustainability [32].
12. Biobased grow bags are used for agricultural practices in home yards, gardens, terraces, and nurseries without any toxic effects [33].
13. Bioplastics are used in the cosmetics industry due to their sustainable and biodegradable nature.
14. Bioplastics in the toy manufacturing industry help protect children from using harmful commercial plastic-based toys [34].

15. The traditional agricultural covers used are nondegradable and harm plants and other vegetation. This can be prevented by using biobased covers that degrade easily and serve as manure for plants [34].

13 Challenges and limitations

1. The produced bioplastics lack any water-resistant qualities [3].
2. When compared to the manufacturing of synthetic plastics, the production of bioplastics is challenging [3].
3. The low biodegradability of PLA biopolymers reduces their use in the production of bioplastics [3].
4. To improve production, upstream and downstream processing of microalgae must be overcome [15].
5. Finding an appropriate microalgae strain to use in the production of bioplastics is challenging [17].
6. Distinct species may have different biomass concentrations, which lowers the production rate [17].
7. PHAs have fewer applications because their production costs are higher than those of synthetic plastics [19].
8. Controlled growth conditions are necessary for microalgal cultivation, and one of the main challenges is the lack of readily available fertilizers [20].
9. In contrast to photobioreactors, open raceway ponds typically have low productivity because of factors such as CO_2 loss, evaporation, contamination, temperature, and seasonal changes [30]
10. The primary drawbacks of these bioplastics are their inherent hydrophilicity and brittleness [31].
11. PHA and PHB bioplastics are only marginally suitable for food packaging due to their brittleness, hardness, thermal instability, and minimal impact resistance [32].
12. The technology for creating bioplastics is still in its infancy. Another significant disadvantage is the lack of technology [34].
13. Another factor in the decreased production of bioplastics is the low level of consumer knowledge about them [34].
14. Toxic substances, such as heavy metals and nonmetal oxides, may be present during the extraction of bioplastics [34].
15. The scale-up process frequently fails because a small-scale technique cannot be applied to a large-scale setting [35].

14 Future prospects

Chlorella sp. and *Spirulina sp.* are the most productive microalgae for making bioplastics. The production of bioplastics from several species of microalgae requires additional study [2]. The majority of bioplastics are made using quite a few chemicals, which might lead to the production of chemical waste. This can be managed by conducting research on the development of bioplastics based on microalgae using green techniques [19]. Additionally, the formation of bioplastics from microalgae can result in the production of useful byproducts such as cosmetics, medicines, nutraceuticals, and fuels. Using fewer chemicals in their production could lead to eco-friendly items that do not have any negative effects on the environment [17]. For customer acceptance, research on the odor of microalgae-based bioplastics can be conducted, effectively increasing the use of bioplastics in food and beverage packaging [17]. Future production of high-quality bioplastics may be facilitated by the introduction of uniform guidelines, specifications, and certifications [17]. The majority of the time, *S. platensis*-derived bioplastics have high tensile strengths but not much elongation [20]. As they are engaged in the plasticizing phenomenon of bioplastics, additional research on the nature of different components in microalgae, such as polysaccharides and macromolecules, such as proteins, is necessary [34]. Genetically engineered strains can be used to create microalgae bioplastics for nonfood goods [34]. The coaccumulation of PHAs, lipids, and carbohydrates in *Scenedesmus sp.* offers the possibility of using this strain to support sustainable and environmentally friendly applications in a variety of sectors [36]. The study of extending the shelf life of bioplastics can expand their use in material packaging and storage [7]. Because of their high production costs, microalgae-based bioplastics are not widely used. To lower the cost of bioplastic production and expand its use globally in the future, new methods and approaches are needed [35].

The promise of sustainable materials that may revolutionize numerous industries by reducing the environmental burden posed by petroleum-based plastics makes the future prospects of microalgae-based bioplastics bright. This vision of a more sustainable and peaceful future needs to be advanced, and everyone has a critical role to play in this: researchers, lawmakers, business executives, and consumers.

15 Conclusion

The exploration of microalgae-derived bioplastics has paved the way for a future that is more environmentally responsible and sustainable. It is evident that microalgae-based bioplastics offer a beacon of hope and opportunity as we stand at the crossroads of developing bioplastic technology and increasing levels of global plastic pollution. We started out by acknowledging the numerous environmental issues that conventional plastics made of petroleum-based materials present. It is obvious that plastic garbage has negative effects, from polluting our oceans to contaminating terrestrial ecosystems. Microalgae-based bioplastics have emerged as a frontrunner in this search for environmentally benign alternatives. Microalgae have shown exceptional potential as a feedstock for bioplastics, despite being frequently underappreciated in the context of sustainable resource management. They are positioned as a sustainable and adaptable option due to their quick growth rates, high lipid content, and capacity to thrive in various environmental circumstances. The circular economy and resource efficiency are embodied in the symbiotic interaction between microalgae and bioplastic manufacturing. We have waded into the complex web of microalgae-based bioplastics in this review, exploring their techniques, characteristics, and potential environmental effects. These bioplastics hold promise not only because they are renewable but also because they have the potential to lessen carbon emissions, advance biodegradability, and prevent the buildup of plastic waste. However, there are obstacles to the widespread use of microalgae-based bioplastics. Strong barriers include technical challenges, economic viability, and regulatory systems. However, these difficulties offer chances for more study and development in the spirit of innovation and sustainability. We are left with a keen sense of optimism and urgency as we reach our destination. The use of microalgae-based bioplastics goes far beyond the purview of research; it is our common duty to usher in a period of sustainable practices and materials. Microalgae-based bioplastics have a bright future full of opportunities, breakthroughs, and partnerships that might completely alter the way materials are produced. Our unequivocal call for action is for researchers, decision-makers, and industry stakeholders to join forces in their determination to investigate, develop, and use microalgae-based bioplastics as the foundation of a more resilient and long-lasting global ecosystem.

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References

1. Abdo SM, Ali GH. Analysis of polyhydroxybutrate and bioplastic production from microalgae. Bull Nat Res Centre. 2019;43(1):1–4. https://doi.org/10.1186/s42269-019-0135-5.
2. Ahmad N, Hamid AN, Osman AM. A review study on the potential of microalgae biomass producing biopolymer material. Current Sci Technol. 2022. https://doi.org/10.15282/cst.v2i2.9413.

3. Trilokchandran B, Vijayakumar G, Thippareddy KS, Binoy A, Bhat D, Bhat JG, Sarvesha Babu M. Algal bioplastics: a review. Ymer. 2022. https://doi.org/10.37896/YMER21.06/09.
4. Boey JY, Mohamad L, Khok YS, Tay GS, Baidurah S. A review of the applications and biodegradation of polyhydroxyalkanoates and poly (lactic acid) and its composites. Polymers. 2021;13(10):1544. https://doi.org/10.3390/polym13101544.
5. Baidurah S. Methods of analyses for biodegradable polymers: a review. Polymers. 2022;14(22):4928. https://doi.org/10.3390/polym14224928.
6. Simonič M, Zemljič FL. Production of bioplastic material from algal biomass. Chem Industry Chem Eng Q. 2021;27(1):79–84. https://doi.org/10.2298/CICEQ191024026S.
7. Ayu GE, Lubis M, Ginting MHS, Hayat N. Physical resistance of corn starch-based bioplastics at various storage temperatures. J Eng Sci Technol. 2023;18(1):235–43. https://doi.org/10.21315/jps2021.32.3.7.
8. Soni P. Comparison between corn and potato starch-based bioplastic: thermal variation. Res Square. 2023. https://doi.org/10.21203/rs.3.rs-3097559/v1.
9. Hamin SH, Abdullah SHYS, Lananan F, Hamid SHA, Kasan NA, Mohamed NN, Endut A. Effect of chemical treatment on the structural, thermal, and mechanical properties of sugarcane bagasse as filler for starch-based bioplastic. J Chem Technol Biotechnol. 2023;98(3):625–32. https://doi.org/10.1002/jctb.7218.
10. Azizati Z, Afidin IMZ, Hasnowo LA. The effect of sorbitol addition in bioplastic from cellulose acetate (sugarcane bagasse)-chitosan. Walisongo J Chem. 2022;5(1):94–101. https://doi.org/10.21580/wjc.v5i1.12173.
11. Mohammed AABA, Hasan Z, Borhana AA, Omran AM, Elfaghi MA, Khattak RA, Ilyas, and S. M. Sapuan. Effect of various plasticizers in different concentrations on physical, thermal, mechanical, and structural properties of wheat starch-based films. Polymers. 2022;15(1):63. https://doi.org/10.3390/polym15010063.
12. Mohammed AA, Hasan Z, Omran AAB, Elfaghi AM, Ali YH, Akeel NA, Ilyas RA, Sapuan SM. Effect of sugar palm fibers on the properties of blended wheat starch/polyvinyl alcohol (PVA)-based biocomposite films. J Mater Res Technol. 2023;24:1043–55. https://doi.org/10.1016/j.jmrt.2023.02.027.
13. Sefrienda AR, Kurnianto D, Jasmadi J, Frediansyah A. Cassava and microalgae use in the food industry: challenges and prospects. Intech Open. 2023. https://doi.org/10.5772/intechopen.110518.
14. Iyer H, Grandgeorge P, Jimenez AM, Campbell IR, Parker M, Holden M, Venkatesh M, Nelsen M, Nguyen B, Roumeli E. Fabricating strong and stiff bioplastics from whole spirulina cells. Adv Funct Mater. 2023. https://doi.org/10.1002/adfm.202302067.
15. Cheah WY, Er AC, Aiyub K, Yasin NHM, Ngan SL, Chew KW, Ling KSKTC, Juan JC, Ma Z, Show PL. Current status and perspectives of algae-based bioplastics: a reviewed potential for sustainability. Algal Res. 2023. https://doi.org/10.1016/j.algal.2023.103078.
16. Senko O, Stepanov N, Maslova O, Efremenko E. Transformation of enzymatic hydrolysates of Chlorella–fungus mixed biomass into poly (hydroxyalkanoates). Catalysts. 2023;13(1):118. https://doi.org/10.3390/catal13010118.
17. Chia WY, Tang DYY, Khoo KS, Lup ANK, Chew KW. Nature's fight against plastic pollution: algae for plastic biodegradation and bioplastics production. Environ Sci Ecotechnol. 2020;4:100065. https://doi.org/10.1016/j.ese.2020.100065.
18. Zatta PHS, Jacob-Furlan B, Mirabile RC, Gonçalves RSR, da Silva PAS, Taher DM, Lira GS, Martins LS, Ordonez JC. Microalgae biopolymers: a review. Revista de Engenharia Térmica. 2023;21(4):44–52. https://doi.org/10.5380/reterm.v21i4.89678.
19. Ranganadhareddy A, Vijetha P, Chandrsekhar C. Bioplastic production from microalgae and their applications-a critical. J Biochem Technol. 2022. https://doi.org/10.51847/H3pUzozErq.
20. Das SK, Sathish A, Stanley J. Production of biofuel and bioplastic from *Chlorella pyrenoidosa*. Mater Today Proc. 2018;5(8):16774–81. https://doi.org/10.1016/J.MATPR.2018.06.020.
21. Cardoso T, Esmerino LA, Bolanho BC, Demiate IM, Danesi EDG. Technological viability of biobased films formulated with cassava by-product and Spirulina platensis. J Food Process Eng. 2019;42(5):e13136. https://doi.org/10.1111/jfpe.13136.
22. Gozan M, Noviasari C. The effect of glycerol addition as plasticizer in Spirulina platensis-based bioplastic. In E3S Web of Conferences. EDP Sci. 2018;67:03048. https://doi.org/10.1051/e3sconf/20186703048.
23. Khalis SA. The effect of compatibilizer addition on Chlorella vulgaris microalgae utilization as a mixture for bioplastic. In E3S Web of Conferences. EDP Sciences. 2018;67:03047. https://doi.org/10.1051/e3sconf/20186703047.
24. Sabathini HA, Windiani L, Gozan M. Mechanical Physicial properties of chlorella-PVA based bioplastic with ultrasonic homogenizer. In E3S Web of Conferences. EDP Sci. 2018;67:03046. https://doi.org/10.1051/e3sconf/20186703046.
25. Dianursanti D, Noviasari C, Windiani L, Gozan M. Effect of compatibilizer addition in Spirulina platensis-based bioplastic production. New York: AIP Publishing; 2019.
26. Rocha CJ, López E-C, Yáñez MRE, Bengoechea C, Guerrero A, Ledesma MTO. Development of bioplastics from a microalgae consortium from wastewater. J Environ Manage. 2020;263: 110353. https://doi.org/10.1016/j.jenvman.2020.110353.
27. Costa SS, Miranda AL, Andrade BB, de Jesus D, Assis CO, Souza MG, de Morais J, Costa AV, Druzian JI. Influence of nitrogen on growth, biomass composition, production, and properties of polyhydroxyalkanoates (PHAs) by microalgae. Int J Biol Macromol. 2018;116:552–62. https://doi.org/10.1016/j.ijbiomac.2018.05.064.
28. Mathiot C, Ponge P, Gallard B, Sassi JF, Delrue F, Le Moigne N. Microalgae starch-based bioplastics: screening of ten strains and plasticization of unfractionated microalgae by extrusion. Carbohydr Polymers. 2019;208:142–51. https://doi.org/10.1016/j.carbpol.2018.12.057.
29. Rueda E, Senatore V, Zarra T, Naddeo V, García J, Garfí M. Life cycle assessment and economic analysis of bioplastics production from cyanobacteria. Sustain Mater Technol. 2023;35: e00579. https://doi.org/10.1016/j.susmat.2023.e00579.
30. Chalermthai B, Charoensuppanimit P, Nootong K, Olsen BD, Assabumrungrat S. Techno-economic assessment of coproduction of edible bioplastic and food supplements from *Spirulina*. Sci Rep. 2023;13(1):10190. https://doi.org/10.1038/s41598-023-37156-3.
31. Narancic T, Cerrone F, Beagan N, O'Connor KE. Recent advances in bioplastics: application and biodegradation. Polymers. 2020;12(4):920. https://doi.org/10.3390/polym12040920.
32. Ibrahim NI, Shahar FS, Sultan MTH, Ain Umaira M, Shah SN, Safri A, Yazik MHM. Overview of bioplastic introduction and its applications in product packaging. Coatings. 2021;11(11):1423. https://doi.org/10.3390/coatings11111423.
33. Coppola G, Gaudio MT, Lopresto CG, Calabro V, Curcio S, Chakraborty S. Bioplastic from renewable biomass: a facile solution for a greener environment. Earth Syst Environ. 2021;5:231–51. https://doi.org/10.1007/s41748-021-00208-7.

34. Liu F, Li J, Zhang XL. Bioplastic production from wastewater sludge and application. IOP Conf Series Earth Environ Sci. 2019;344(1):012071. https://doi.org/10.1088/1755-1315/344/1/012071.
35. Acién Fernández FG, Sevilla JMF, Grima EM. Costs analysis of microalgae production. 21st ed. Almería: Department of Chemical Engineering, University of Almería; 2020.
36. García G, Sosa-Hernández JE, Rodas-Zuluaga LI, Castillo-Zacarías C, Iqbal H, Parra-Saldívar R. Accumulation of PHAs in the microalgae *Scenedesmus sp*. Under nutrient-deficient conditions. Polymers. 2020;13(1):131. https://doi.org/10.3390/polym13010131.
37. Sreenikethanam A, Bajhaiya A. Algae based bio-plastics: future of green economy. Biorefineries-Selected Process. 2021;9(4):77–89. https://doi.org/10.5772/intechopen.100981.
38. Chamas A, Moon H, Zheng J, Qiu Y, Tabassum T, Jang JH, Abu-Omar M, Scott SL, Suh S. Degradation rates of plastics in the environment. ACS Sustain Chem Eng. 2020;8(9):3494–511. https://doi.org/10.1021/acssuschemeng.9b06635?ref=pdf.
39. Porri L, Giarrusso A. Conjugated diene polymerization. Compr Polymer Sc. 1989;4:53–108. https://doi.org/10.1016/B978-0-08-096701-1.00120-8.
40. Mohan AA, Antony AR, Greeshma K, Yun JH, Ramanan R, Kim HS. Algal biopolymers as sustainable resources for a net-zero carbon bioeconomy. Biores Technol. 2022;344:126397. https://doi.org/10.1016/j.biortech.2021.126397.
41. Kalita NK, Damare NA, Hazarika D, Bhagabati P, Kalamdhad A, Katiyar V. Biodegradation and characterization study of compostable PLA bioplastic containing algae biomass as potential degradation accelerator. Environ Chall. 2021;3:100067. https://doi.org/10.1016/j.envc.2021.100067.
42. Rosenboom J-G, Langer R, Traverso G. Bioplastics for a circular economy. Nat Rev Mater. 2022;7(2):117–37. https://doi.org/10.1038/s41578-021-00407-8.
43. Ali WS, Zaki NH, Obiad SYN. Production of bioplastic by bacteria isolated from local soil and organic wastes. Curr Res Microbiol Biotechnol. 2017;5(2):1012–7.
44. Sofian BA, Aiman AD, Lim HR, Manickam S, Ang WL, Show PL. Towards a sustainable circular economy: algae-based bioplastics and the role of internet-of-things and machine learning. Chem Bio Eng Rev. 2023. https://doi.org/10.1002/cben.202300028.
45. Simó-Cabrera L, García-Chumillas S, Hagagy N, Saddiq A, Tag H, Selim S, AbdElgawad H, et al. Haloarchaea as cell factories to produce bioplastics. Mar Drugs. 2021;19(3):159. https://doi.org/10.3390/md19030159.