Algal Bio-Mulch : A Comprehensive Review On Production, Characterization and Applications in Sustainable Agriculture

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Abstract - Sustainable agriculture necessitates innovative solutions to reduce environmental impact while enhancing productivity. Algal-based bio-mulch has been shown to be a highly potential eco-friendly option based on its biodegradable nature, renewable feedstocks, and potential to enrich soils. The investigation here centers around algal species selection, processing of bio-mulch films, and comparative assessment with synthetic and other bio-based mulches. Physical, mechanical, and thermal characteristics of the bio-mulch made from algae are tested, as well as its functioning in farming conditions. In addition, biodegradation tests measure its degradation rate in the ground and how it affects microbial growth. The findings identify the merits and demerits of algal-based bio-mulches, highlighting their prospects in sustainable agriculture while mitigating environmental impacts of conventional mulch films.

Key Words: Algal-based bio-mulch, Eco-friendly, bio-mulch films, Sustainable agriculture, Biodegradation.

1. INTRODUCTION

The Agricultural sector has historically relied on plastic-based mulches to increase crop yields through moisture control, weed suppression, and soil temperature regulation. The environmental effects of non-biodegradable plastic mulches have become a major concern, leading to long-term agricultural ecosystem pollution (Anderson et al., 2017). This has led to the quest for sustainable options, with a specific focus on investigating biodegradable bioplastics from algae. Algal-based bio-mulch offers an alternative that unites the advantages of conventional plastic mulching with the ecological-friendly nature of biodegradability. Of the range of algae options, Spirulina and Chlorella stand out as key contenders for use as bioplastics because they have high growth rates, contain high levels of nutrients, and can be cultured to produce bioactive compounds that can be treated to create functional materials (Lee et al., 2020). Arthrospira platensis is renowned for having high protein levels, which can be used in bioplastic manufacture. Likewise, Chlorella vulgaris is known for its lipid and carbohydrate levels, which play a positive role in the mechanical strength of bioplastics. There has been research to show the viability of utilizing these microalgae in the manufacture of bioplastics, pointing to their viability in the production of sustainable materials.

The choice of the right algal species is important for maximizing bioplastic production. Studies have considered the potential of Spirulina and Chlorella for the production of bio-mulch by analyzing their biomass yield, growth conditions, and cell structure (Kumar et al., 2018). The production of algal-based bio-mulch involves converting these algal species into films or coatings that have mechanical properties, including tensile strength, flexibility, and water retention. Several research works have aimed at the processing of algae into bioplastics through some techniques such as solvent casting, extrusion, and compression molding (Yuan et al., 2021).

Another significant factor to consider is algal-based bio-mulch degradation. Biodegradable mulch should degrade within soil conditions and not leave harmful residues. A recent study illustrated that algal bio-mulch can degrade when exposed to normal soil conditions, enhancing soil vitality and microbial content while minimizing pollution (Liu et al., 2023). The rate of degradation of Spirulina and Chlorella bio-mulch is affected by a range of variables such as environmental conditions, microbial activity, and material composition (Zhang et al., 2024). Moreover, research has underscored the capability of algae to enhance soil structure through releasing vital nutrients during decomposition, thus supporting sustainable agriculture (Singh et al., 2019).

1.1 ALGAE AS BIOPOLYMER

Algae, or microalgae and macroalgae, have been a promising option for the production of biopolymers because they grow fast, produce high biomass yields, and can synthesize various biopolymers. These biopolymers, including polysaccharides such as alginate, agar, and carrageenan, and polyhydroxyalkanoates (PHAs), have promising uses in different industries. Biopolymers derived from algae not only decrease the reliance on fossil fuels but also offer a sustainable and environmentally friendly alternative to the plastic problem worldwide (Smith et al., 2020).

The manufacture of biopolymers from algae encompasses a number of important steps: cultivation, harvesting, extraction, and processing. Improvements in cultivation methods, including the utilization of photobioreactors and the optimization of growth conditions, have enhanced biomass productivity. Effective extraction processes, including physical, chemical, and enzymatic methods, have been established to recover high-purity biopolymers from algal biomass. Processing methods enables the fabrication of these biopolymers into appropriate forms for particular applications. Following the increasing need for eco-friendly materials, algae-based bioplastics have become increasingly popular in research work at both academia and industry levels (Zhang et al., 2022). Algae yield a variety of natural polymers, including polysaccharides (e.g., alginate, agar, carrageenan), proteins, and polyhydroxyalkanoates (PHAs), which have a wide range of applications across different industries (Jones & Brown, 2019). At the packaging sector, such polymers are employed to create degradable films and coatings, thus minimizing dependence on petrochemical plastics. In the biomedical sector, alginate and carrageenan are utilized in wound dressings, drug delivery systems, and tissue engineering scaffolds because of their biocompatibility and gel-forming capabilities. Algae mulch films, seed coatings, and controlled-release fertilizers also play a role in better soil health and crop yields, ensuring sustainable agriculture (Patel & Verma, 2020).

1.2 ALGAE AS BIOMULCH

Algae are being considered in agriculture for their ability to be used as bio-mulch because of their nutrient density, water-holding capacity, and biodegradability. Using algae as bio-mulch takes advantage of their natural growth habits and the profusion that occurs in coastal and aquatic ecosystems, where they can be harvested in a sustainable manner. In agricultural environments, algae serve not only as soil moisteners but also promote vegetation by providing nutrients necessary for plant growth, thus minimizing the use of chemical fertilizers and enhancing soil structure. This method proves especially useful in arid or semi-arid conditions where water savings are paramount.

Algae have a high nutrient content of nitrogen, phosphorus, potassium, and trace elements such as magnesium and iron. Decomposing algae releases these nutrients slowly into the soil, promoting plant growth and reducing chemical fertilizer dependence even more (Tsiropoulos et al., 2019). Algal-mulch is increasingly becoming popular in sustainable agriculture because of its many agronomic and environmental advantages. Being a natural and biodegradable material, algae are a substitute for plastic and synthetic mulches, providing benefits like enhanced soil fertility, water retention, weed control, and carbon sequestration. The mulch cover retains soil moisture by minimizing evaporation, thus being particularly useful in arid areas (Chung et al., 2021). Apart from the retention of moisture, mulches developed from algae inhibit weed growth through the physical barrier and the release of allelopathic chemicals that interfere with the growth and germination of intrusive weeds, hence minimizing the application of herbicides (Guedes et al., 2022). Algae decomposition further increases soil microbial diversity and facilitates beneficial microbial activity, enhancing the structure of the soil and organic matter content (Mann et al., 2020). In addition, algae helps in sequestering carbon by trapping CO_2 in the atmosphere while they grow. As mulch, they release carbon into the soil over time, which aids in long-term soil well-being (Sato et al., 2021).

2. SELECTION AND FABRICATION OF ALGAL BIOMASS

Microalgae are photosynthetic microorganisms with high biomass yields and high growth rates. They are able to grow in diverse environments. In current agriculture, there is a growing demand for biodegradable mulching agents that can replace synthetic plastic mulches, which are responsible for environmental contamination (Scarascia-Mugnozza et al., 2012). Algal biomass has been identified as a viable substitute because of its high organic content and capacity to improve soil quality (Kumar & Sahoo, 2022).

The choice of microalgal biomass is a significant process that is based on the purpose of use, i.e., production of biofuels, food supplements, bioremediation, or crop products like bio-mulch. Some of the major factors governing the choice include the growth rate of the species, tolerance of the environment, and biochemical constitution. Rapid-growing species like Chlorella vulgaris, Arthrospira platensis, and Scenedesmus obliquus are usually preferred because of their high biomass production and tolerance for changing environmental conditions (Chisti, 2007). Fast-growing species and a proper biochemical composition—such as polysaccharides to provide structural stability are preferred. Chlorella vulgaris and Arthrospira platensis are mostly preferred because they have high productivity and nutrient yields (Chisti, 2007; Borowitzka, 2013).

Motasem Alazaiza et al. (2023) has observed that biopolymers are often manufactured by methods like electrospinning and melt casting. In recent times, the popularity of bio-composite materials or green composites has seen as future substitutes for conventional materials in manufacturing. Researchers are becoming more and more interested in bio-composites due to their benefits over traditional synthetic materials such as compostability upon use, disposal convenience, and sustainability due to being renewable resources. In addition, bio-composites can be utilized across a broad scope of applications owing to their similar mechanical properties.

Subhash et al. (2022) discovered that algal-based biopolymers out-perform petroleum-based biopolymers in mechanical properties. Algal biopolymers can be further improved with additives, plasticizers, and compatibilizers, added to increase intermolecular interaction between the different compounds to make the material stronger, flexible, and long-lasting. This research focussed on presenting an extensive overview of the latest developments in algae biopolymers in the context of a sustainable circular economy and highlights the production of these biopolymers from microalgae. This work also elaborates on the algae circular bioeconomy based on the problems being encountered by the biopolymer sector today. Furthermore, the study extensively scale-up problems and the cost of operation of culture systems to highlight the challenges faced in algal biomass production.

2.1 PRODUCTION OF BIOPOLYMERS

Kumari Pooja et al. (2022) observed that cyanobacteria can accumulate polyhydroxybutyrate (PHB), a molecule used as an intracellular energy and storage of carbon. In a study in 2016, researchers established the PHB levels of 137 cyanobacterial strains, 88 species in 26 taxa, under photoautotrophic growth conditions. The findings showed that high PHB content was strain-specific and not linked to the genus. The strain produced 356.6 mg/L of PHB in 44 days, which is equivalent to a PHB content of 25% of its cell dry weight (cdw) and a total biomass of 1.4 g/L. In nitrogen depletion, the cells had a concentration of PHB at 25%, while under nitrogen-replete conditions, the PHB level decreased to a mere 0.4%.

Savvas Giannis Mastropetros et al. (2022) stated that microalgae are capable of synthesizing poly(hydroxyalkanoate) (PHA) esters, which are aliphatic polyesters that are biodegradable. The most common and extensively characterized biopolymer in this group is poly(3-hydroxybutyrate) (PHB), a short-chain PHA. PHB degrades completely to carbon dioxide and water when it is oxidized aerobically, making it environmentally friendly. PHB also has thermal and mechanical characteristics similar to petrochemical polymers.

Olga Kronusova et al. (2022) found that the freshwater green microalgae Dictyosphaerium chlorelloides (CCALA 330) are able to produce extracellular polysaccharides (EPS). Optimal growth and increased EPS production were found in laboratory-scale tubular photobioreactors (PBR) with a 300 mL working volume. It was found that the application of multiple limitations for nutrient supply was an efficient approach to enhance overproduction of EPS. Though salinity stress was also imposed on the culture, it also did not result in increased EPS production.

The impact of different nitrogen sources on the growth of microalgae was investigated, and it was found that the highest growth rate and extracellular polymeric substance (EPS) production were in a medium with ammonium nitrate. A new and efficient way to separate cells from the EPS-rich culture broth was established. Because of the strong adhesion between the cells and the EPS, high-pressure homogenization was used before centrifugation. The EPS was subsequently purified from the supernatant by ultrafiltration. Thus, Dictyosphaerium chlorelloides has potential for industrial EPS production.

2.2 MICROALGAE AND ITS ADDITIVES

Rozita Madadi et al. (2021) pointed out that blending polymers is a useful technique for improving the properties of polymeric materials. Various research on polyhydroxyalkanoates (PHA) has been aimed at their improvement in properties and decreasing their cost of production. Biodegradable polymers such as cellulose, lignin, amylose, amylopectin, polylactic acid (PLA) and polycaprolactone are usually blended with PHAs to result in enhanced properties. Cellulose derivatives such as ethyl cellulose and cellulose acetate butyrate show high compatibility with PHAs and thus can be blended. Short-chain-length PHAs (scl-PHAs) have a tendency to be brittle and highly crystalline, which restricts their flexibility as biomaterials.

Besides, Spirulina and Chlorella were introduced into the high-density polyethylene (HDPE) blends of thermoplastic. Between these, Spirulina displayed better outcomes when considering the resultant properties of the thermoplastic blends. Contrary to conventional fossil-derived plastics, bioplastics made of microalgae are possible for being engineered biodegradable under both natural composting environments as well as industrial composting facilities. The predominantly utilized classes among those already developed for bio-based plastics are the ones made up of starch, polyhydroxyalkanoates (PHAs), polylactic acid (PLA), and cellulose. PLA is one of the most well-researched bioplastics in terms of recyclability. Polylactic acid (PLA) is a thermoplastic obtained through the condensation of lactic acid or the ring-opening polymerization of lactide. PLA offers high mechanical strength and great thermal properties relative to other fossil-based polymers. The character of the amorphous PLA, such as its glass transition and aging process mechanisms, was explored by Marjana Simonic et al. (2020).

Shui-Ping Chang et al. (2015) published the extraction and analysis of exopolysaccharides (EPS). Sotalia fluviatilis is a dominant freshwater macro-green alga with high possibilities for EPS extraction in its natural environment. He contrasted the EPS extraction yields from the mucilage layer of Sotalia fluviatilis by two chemical methods (formaldehyde-NaOH and NH4OH) and two physical methods (ultrasonication and heating). The results showed that EPS (both proteins and polysaccharides) could be effectively extracted using the heating method. The protein to polysaccharide ratios of heat-extracted EPS (TB-EPS) were significantly different from one another, whereas the same could not be said in the case of liquid-buffer extracted EPS (LB-EPS). Additionally, the method of extraction of macroalgal EPS can affect the rate of extraction, composition, and characteristics.

2.3 COMPARATIVE ANALYSIS

Spirulina (Arthrospira platensis) contains high protein content, which constitutes 60-70% of the dry weight. This trait can increase soil fertility when applied as biomulch (Borowitzka, 2013). Spirulina also contains a high content of polysaccharides, which impart structural strength to biomulch films (González-González et al., 2021).

Chlorella (Chlorella vulgaris) also possesses a well-balanced protein, lipid, and carbohydrate composition (Chisti, 2007) and is rich in polysaccharides, although it contains lower protein content compared to Spirulina (Zhu, 2015).

As per Mark Ashton Zeller et al. (2013), Spirulina and Chlorella can be employed in order to produce algal-based bioplastics and blends of thermoplastics. The algal protein biomass can be cultivated with nutrient wastewater from livestock farms or municipal and industrial effluents, which will help to remediate excess nitrogen and phosphorus. These algal bioplastics are biodegradable and can be designed to have a broad range of properties to fit different uses, such as edible and disposable plastic items, plastic items in agriculture, and horticultural plant pots. Experimental findings suggest that some of the most important variables influencing polymerization and structure stabilization in the compression molding process of algal protein biomass and thermoplastic blends are pressure, temperature, plasticizer concentration, and processing time. Chlorella has shown better bioplastic characteristics than Spirulina, whereas Spirulina is better in blends.

2.4 BIODEGRADATION STUDIES

Decomposition of algal bio-mulch is assisted by soil microbes that degrade polysaccharides, proteins, and lipids into simpler nutrients (González-González et al., 2021). In the process of biodegradation, vital nutrients like nitrogen, phosphorus, and potassium are released into the soil, improving its fertility (Borowitzka, 2013). Spirulina bio-mulch decomposes more quickly due to its high content of protein and polysaccharides, which are readily metabolized by microbes in the soil (Chisti, 2007). The decomposition release of nitrogenous compounds also increases soil fertility and plant growth (Rawat et al., 2011). Moreover, Spirulina bio-mulch is completely biodegradable and toxic residue-free, thus it is an environmentally friendly option compared to chemical mulch (Ugwu et al., 2008).

Conversely, Chlorella bio-mulch is moderately degradable because of its balanced structure of proteins, lipids, and carbohydrates (Zhu, 2015). Its slow release of nutrients sustains long-term soil fertility and microbial populations (González-González et al., 2021). Similar to Spirulina, Chlorella is also completely biodegradable and promotes sustainable agriculture (Borowitzka, 2013).

Spirulina is more degradable than Chlorella due to its greater protein and polysaccharide content. It gives instant improvement to soil quality by releasing nutrients rapidly, whereas Chlorella provides a gradual, slow release of nutrients for long-term soil enrichment (Zhu, 2015). Both are eco-friendly and completely biodegradable; however, Spirulina can be more applicable for short-term use, while Chlorella is best for long-term soil enrichment (González-González et al., 2021).

2.5 BIOLOGICAL APPLICATIONS:

Suolian Guo et al. (2020) explained that bioplastics have great potential as living resources in numerous applications, such as medicine, health products, animal feed, and fuel. Such organisms can further be used in contemporary agriculture because they are capable of enrichment of soil nutrients as well as increased utilization of both macro and micronutrients. Besides enhancing soil fertility and quality, microalgae are capable of producing plant growth hormones, polysaccharides, antimicrobial substances, and other metabolites that enhance plant growth. This section highlights the impact of cyanobacteria and green algae as biofertilizers in enhancing soil fertility and quality and enhancing plant growth. Recent advances in research and future directions in their use in contemporary agriculture are also presented.

Ammar et al. (2022) emphasized that bio-fertilization is an eco-friendly agricultural practice that employs bio-fertilizers to increase soil nutrients and productivity. Microflora of the soil are important for increasing fertility and biomass productivity and act as good and eco-friendly fertilizers. Some cyanobacteria, such as Anabaena sp., and Nostoc sp., have the ability to fix atmospheric nitrogen and are known as good bio-fertilizers. Well-known microalgae species like Acutodesmus dimorphus, Spirulina platensis, and Chlorella vulgaris also stimulate crop development. In addition, seaweed species like Sargassum sp. and Gracilaria verrucosa can increase indicators of soil fertility in sandy soils through organic matter accumulation and the normalization of pH values.

Aluru Ranganadha Reddy (2022) indicated that biopolymers have the characteristic of renewability, biocompatibility, and biodegradability. Biobased plastics are becoming of growing interest to be used in energy, medical devices, electronics, and food packaging. Biopolymers can be derived from biological sources such as microbes, agricultural waste, animals, and plants.

Maheswari et al. (2011) pointed out that problems related to the non-biodegradability of conventional plastics, the shortage of landfill dumps, and the increasing issue of water and soil pollution have compelled concern over plastic utilization. Maheswari et al. (2011) extracted a bioplastic from Spirulina platensis grown in the modified Zarrouk medium by maximizing the level of polyhydroxybutyrate (PHB) in S. platensis by adding sodium acetate into the optimized growth medium. Total dry weight and PHB content were measured with a UV spectrophotometer before and after optimization. The findings indicated that the optimized medium gave a slightly higher PHB content (6.20%) than the untreated medium (5.18%). Bioplastic was prepared after harvesting S. platensis. The biodegradation characteristics and expenses were assessed by analyzing the composition. Results showed that plasticizing and moldability characteristics of all the manufactured plastics were good. On biodegradation, S. platensis bioplastic was better because of the PHB content, but it was more expensive to use S. platensis than other chemical and organic polymers.

3. CONCLUSION:

Algal bio-mulch is a green and sustainable substitute for conventional mulch materials. It has enormous advantages in terms of soil health, crop yield, and conservation of the environment. Selection of appropriate microalgal species, Spirulina and Chlorella is relied based on parameters such as growth rate, biochemical makeup, and tolerance to the environment.

The process of production includes growing, harvesting, and processing the algae, which has been maximized to produce long-lasting and nutrient-dense bio-mulch. Photo-bioreactor and hybrid system advancements have enhanced biomass yield and economic efficiency. Comparative analyses proves that Spirulina breaks down faster, releasing nutrients immediately, whereas Chlorella has a gradual rate of degradation, which maintains soil fertility over time. Biodegradation tests validates that both algae are completely biodegradable, releasing vital nutrients like nitrogen and phosphorus into the soil without toxic residue. Generally, algal-based bio-mulch is highly promising to transform sustainable agriculture, subject to the overcoming of current technological and economic limitations by continued research and innovation.

REFERENCES

1. N.Johnsson , F.Steuer . Bioplastic Material from Microalgae: Extraction of Starch and PHA from Microalgae to Create a Bioplastic Material. KTH Royal Institute of Technology; Stockholm, Sweden: 2018.
2. S.Behera, M.Priyadarshanee, Vandana, and S.Das, (2022). Polyhydroxyalkanoates, the bioplastics of microbial origin: Properties, biochemical synthesis, and their applications. Chemosphere, Vol.294, p.133723.
3. S.K Bhatia, R.Gurav, T.R Choi, H.R Jung, S.Yang, Y.Moon, H.S Song, Jeon, K.Choi and Yang, (2019). Bioconversion of plant biomass hydrolysate into bioplastic (polyhydroxyalkanoates) using Ralstoniaeutropha 5119. Bioresource Technology, Vol.271, pp.306-315.
4. B.T Dang, X.T Bui, D.P Tran, D. Hao, H.Ngo, N. Hoang, P.T Nguyen ,C. Lin, (2022). Current application of algae derivatives for bioplastic production: A review Bioresource Technology, Vol.347, p.126698.

5. S.Daniel, L.Amanda, Adriana and Mario (2020). Approaching the environmental problem of microplastics: Importance of WWTP treatments. Science of the Total Environment, Vol.740, p.140016.
6. N.Zhu, M.Ye, D.Shi D, M.Chen. Reactive compatibilization of biodegradable poly(butylene succinate)/Spirulina microalgae composites. Macromolecules. Res. 2017, pp.165–171.
7. B.S. McSwain, R.L. Irvine, M. Hausner, and P.A. Wilderer, "Composition and distribution of extracellular polymeric substances in aerobic flocs and granular sludge," Appl. Environ. Microbiology. vol. 71, pp. 1051–1057, 2004.
8. L. Gao, X.L. Pan, D.Y. Zhang, S.Y. Mu, D.J. Lee, and U. Halik, "Extracellular polymeric substances buffer against the biocidal effect of H2O2 on the bloom-forming cyanobacterium Microcystis aeruginosa," Water Res. vol. 69, pp. 51-58, 2015.
9. F. Freitas, V.D. Alves, J. Pais, N. Costa, C. Oliveira, and L. Mafra, "Characterization of an extracellular polysaccharide produced by a Pseudomonas strain grown on glycerol," Bioresource Technology. vol. 100, pp. 859–865, 2009.
10. Z. Chi, C.D. Su, and W.D. Lu, "A new exopolysaccharide produced by marine Cyanothece sp. 113.," Bioresource Technology. vol. 98, pp. 1329– 1332, 2007.
11. M. Lundkvist, U. Gangelhof, J. Lunding, and M.R. Flindt, "Production and fate of extracellular polymeric substances produced by benthic diatoms and bacteria: A laboratory study," Estuar. Coast. Shelf Sci. vol. 75, no. 3, pp. 337-346, 2007.
12. R. Jain, S. Raghukumar, R. Tharanathan, and N.B. Bhosle, "Extracellular polysaccharide production by Thraustochytrid Protists," Marine Biotechnology. vol. 7, pp. 184–192, 2005.
13. A.S. Kumar, K. Mody, and B. Jha, "Bacterial exopolysaccharides—a perception," J. Basic Microbiol. vol. 47, pp. 103–117, 2007.
14. M. Avinash, K. Kumari, and J. Bhavanath, "Characterization of extracellular polymeric substances produced by micro-algae Dunaliella salina," Carbohydrate. Polymer. vol. 83, pp. 852–857, 2011.
15. A.Rahman ,R.J Putman, K. Inan, F.A Sal , A. Sathish, T.Smith , C.Nielsen ,R. Sims ,D.Miller . Polyhydroxybutyrate production using a wastewater microalgae based media. Algal Res. 2015, pp.95- 98.
16. A.Singh, L.Sharma, N.Mallick, J.Mala. Progress and challenges in producing polyhydroxyalkanoate biopolymers from cyanobacteria. J. Appl. Phycol. 2017, pp. 1213–1232.
17. J.Kaparapu Polyhydroxyalkanoate (PHA) Production by Genetically Engineered Microalgae: A Review. J. New Biol. Rep. 2018, pp. 68–73.
18. K.Wang, A.Mandal, E.Ayton, R. Hunt, M.Zeller, S.Sharma . Protein Byproducts. Academic Press; Cambridge, MA, USA: 2016. Chapter 6—Modification of Protein Rich Algal-Biomass to Form Bioplastics and Odor Removal; pp. 107–117.
19. M.Charlie, P.Pauline, G.Benjamin, S.Jean-François, D.Florian, L.M.Nicolas . Microalgae starch-based bioplastics: Screening of ten strains and plasticization of unfractionated microalgae by extrusion. Carbohydr. Polym. 2019, pp. 142–151.
20. A.Rahman and D.Miller. Microalgae as a Source of Bioplastics. In Algal Green Chemistry; Elsevier: Amsterdam, The Netherlands, 2017, pp. 121–138.
21. C.S.Onen, Z.K.Chong, M.Kucuker, N.Wieczorek, K.Kuchta. Bioplastic Production from Microalgae: A Review. Int. J. Environ. Res. Public Health 2020.
22. S.Lambert and M.Wagner Environmental Performance of Bio-Based and Biodegradable Plastics: The Road Ahead. Chem. Soc. Rev. 2017, pp. 6855–6871.
23. A.Raza, S.Abid, M.Banat, Polyhydroxyalkanoates: Characteristics, Production, Recent Developments and Applications. Int. Biodeterior. Biodegradable 2018, pp.45–56.
24. S.Balaji, K.Gopi, B.Muthuvelan. Review Article: A Review on Production of Poly β hydroxybutyrates from Cyanobacteria for the Production of Bioplastics. ALGAL 2013, pp.278–285.
25. K.Zhao,Y.Deng, J.Chun Chen, G.Chen Polyhydroxyalkanoate (PHA) Scaffolds with Good Mechanical Properties and Biocompatibility. Biomaterials 2003, pp. 1041–1045.
26. B.Bayon, R.Berti, M.Gagneten, R.Castro Biopolymers from Wastes to High-Value Products in Biomedicine. In Waste to Wealth. Energy, Environment, and Sustainability; Springer: Singapore, 2018, pp. 1–44.
27. E.Bugnicourt, P.Cinelli, A.Lazzeri, V.Alvarez, Polyhydroxyalkanoate (PHA): Review of Synthesis, Characteristics, Processing and Potential Applications in Packaging Express Polym. Lett. 2014, pp. 791–808.
28. A.Kovalcik, K.Meixner, W.Zeilinger, I.Fritz, W.Fuchs, F.Stelzer, B.Drosg Characterization of Polyhydroxyalkanoates Produced by Synechocystis salina from Digestate Supernatant. Int. J. Biol. Macromolecules. 2017, pp. 497–504.
29. I.Noda, P.R.Green, M.Satkowski, L.A.Schechtman. Preparation and Properties of a Novel Class of Polyhydroxyalkanoate Copolymers. Biomacromolecules 2005, pp.580–586.
30. R.Carpine, G.Olivieri, K.J.Hellingwerf, A.Pollio, A.Marzocchella. Industrial Production of Poly-β-hydroxybutyrate from CO2: Can Cyanobacteria Meet this Challenge Processes 2020, volume 8, p.323.
31. S.Costa, L.Miranda, G.Morais, J.Costa, J.Druzian,. Microalgae as Source of Polyhydroxyalkanoates (PHAs)—A Review. Int. J. Biol. Macromol. 2019, pp. 536–547.
32. S.Ummalyma, D.Sahoo, A.Pandey. Microalgal Biorefineries for Industrial Products. In Microalgae Cultivation for Biofuels Production; Elsevier: Amsterdam, The Netherlands, 2020, pp. 187–195.