engineering proceedings

Proceeding Paper

Biomaterials: A Sustainable Solution for a Circular Economy †

Jayana Rajvanshi [1], Monika Sogani [1,*], Anu Kumar [2] and Sudipti Arora [3]

1 Department of Biosciences, Manipal University Jaipur, Jaipur 303007, Rajasthan, India; rajvanshi97@gmail.com
2 The Commonwealth Scientific and Industrial Research Organization (CSIRO), L&W, Waite Campus, Urrbrae, SA 5064, Australia; anupama.kumar@csiro.au
3 Dr. B. Lal Institute of Biotechnology, Malviya Industrial Area, Malviya Nagar, Jaipur 302017, Rajasthan, India; sudiptiarora@gmail.com
* Correspondence: monika.sogani@jaipur.manipal.edu; Tel.: +91-9414207450

† Presented at the International Conference on Recent Advances on Science and Engineering, Dubai, United Arab Emirates, 4–5 October 2023.

Abstract: A few of the reasons behind the introduction of the concept of biomaterials, such as biopolymers to address problems like plastic pollution, include a lower reliance on fossil resources, reduced carbon emissions, a focus on non-renewable resource allocation, and, most importantly, promoting a circular economy. The high production cost is a hindrance in scaling up the production and market for biobased and biodegradable plastics, but microbial production of such monomers or polymers using easily available and inexpensive substrates, like waste streams, can be seen as a potential strategy to overcome this challenge. These polymers, with properties similar to conventional plastics, can be applied as alternatives in different sectors. According to the Intergovernmental Panel on Climate Change (IPCC), climate change now requires immediate mitigation. Looking at this need, the construction industry has started using biobased materials to focus on reducing CO_2 emissions. Similarly, the improved barrier, mechanical, antimicrobial, and antioxidant properties; biocompatibility; and biodegradability of biomaterials like PLA, PHA, etc., make them suitable for various other sectors. The present paper will focus on highlighting the multi-functionality of such biobased materials that will further open many opportunities for significant innovation.

Keywords: biobased plastics; biodegradable; microbial production; substrates; plastic pollution

Citation: Rajvanshi, J.; Sogani, M.; Kumar, A.; Arora, S. Biomaterials: A Sustainable Solution for a Circular Economy. *Eng. Proc.* **2023**, *59*, 133. https://doi.org/10.3390/engproc2023059133

Academic Editors: Nithesh Naik, Rajiv Selvam, Pavan Hiremath, Suhas Kowshik CS and Ritesh Ramakrishna Bhat

Published: 30 December 2023

1. Introduction

Sustainability is a fundamental concept in comprehending a circular economy and its vital role in society and the overall economy. A circular economy is an attempt to replicate nature's ability to close loops in artificial systems. It is based on maximizing the value of resources indefinitely, which necessitates almost no unrecoverable waste. It is critical to avoid unsustainable resource usage, product redundancy, uncontrolled waste generation, and pollution. In the European Union (EU), policies promoting renewable energy and biobased goods have increased the relevance of biomass feedstocks. This has helped to establish the conditions for a circular economy by utilizing renewable materials. Overall, the concept of a circular economy aims to move away from the traditional linear economic model of "take, make, dispose" and focus on creating products, materials, and systems that promote sustainability, minimize waste, and maximize resource efficiency [1].

Plastics derived from petroleum are a major source of global pollution since they persist in the environment for hundreds of years after their disposal. The current process of producing, using, and disposing of plastics is not utilizing the economic benefits of a circular approach and is causing significant damage to the environment. It is crucial to identify the European countries that are efficient in plastic product end-of-life processes, determine the reasons behind inefficiencies, and find ways for less efficient countries to direct their efforts towards a more circular economy [2]. Current plastic production has reached over 430 million metric tons per year [3]. Their increased durability, improved electrical and thermal properties, and good resistance have made plastic the material of choice for industrial as well as domestic systems. However, 80% of this plastic is coming back into the environment as waste because of improper disposal and management [4]. Current management approaches like landfilling of plastic waste contaminate groundwater and degrade soil, and subsequently, the waste enters the food chain. Another approach is incineration which contributes to global warming, heavy metal contamination of soil, and health issues. Recycling can be the most efficient method of plastic waste management but is found to be very inconsistent [5]. This scenario has led to the idea of developing biomaterials like biodegradable or biobased plastics as a substitute for conventional petroleum-based plastics. Scientists are currently investigating the use of biobased plastics as a feasible substitute for conventional plastics to maintain the advantageous and fundamental physical attributes present in petrochemical-derived plastics. With properties similar to traditional plastic material, biodegradable plastics also have a lower CO_2 impact on the environment, as long as their use is coupled with proper waste management. To address challenges in plastic waste management or controlling plastic pollution, the demand for low-cost, environmentally friendly plastic material is increasing [6]. The key qualities linked to a sustainable product are biodegradability, energy savings, and the use of renewable resources for production. Bioplastic is a broad term that covers bio-based and biodegradable, or both, polymers. Such plastics are growing at a pace of 10% per year, accounting for approximately 10–15% of the total plastics industry [7]. Furthermore, they are used as polymers that will eventually constitute the structural part of a final product, such as functional polymers such as inks, adhesives, and coatings, or also as a performance enhancer [7]. This shift towards biobased plastics presents an opportunity for a circular economy, resulting in a reduced dependence on fossil fuel consumption, and also addresses the global plastic pollution crisis, leading to a cleaner environment. This also targets sustainable development goal no. 11, promoting inclusive, safe, resilient, and sustainable cities and human settlements. The success of such plastics depends on the sustainability credentials, resources, technology, regulations, and consumers [6]. This plastic type can have different biobased origins like casein, lignin, protein, chitosan, cellulose, starch, etc. [8,9]. Polyhydroxyalkanoate (PHA) is the most common type of biobased polymer, which is produced by various microbes, and serves as a storage material for energy and carbon. The biodegradability and favorable material properties have made PHA a potential alternative to non-degradable petro-based plastics [10]. The motivation behind adopting biodegradable plastics over conventional ones is the environmental benefits in terms of a reduced reliance on fossil fuels, less greenhouse gas (GHG) emissions, a reduced carbon footprint, and faster degradation. Also, their end products can be used as raw materials, which avoids the need for new raw materials and provides multiple end-of-life options [7,9]. The degradation approach of such plastic materials depends on their chemical properties and environmental conditions. Various microbes, including fungi, algae, and bacteria, tend to naturally mineralize biobased polymers into water, CO_2, methane, and other inorganic matter [11]. The use of such materials makes it possible to reduce the carbon footprint associated with conventional, long-established plastics. As a result, choosing biobased plastics instead of fossil-based plastics is increasingly important to decrease our dependence on fossil fuels [12]. Although they are the most important production feedstock, fossil fuels are not renewable and contribute to climate change by releasing GHGs like CO_2. However, switching from a petroleum refinery model to one that uses waste as the principal feedstock can significantly manage carbon and reduce GHGs.

A Life Cycle Assessment (LCA) is a key tool to measure the environmental impact of products or services. LCAs of biobased plastics show that such biomaterials enable a significant CO_2 saving (up to carbon neutrality) compared to conventional plastics, depending on the feedstock, the product, and its application. The present review outlays the need to replace fossil-fuel-based plastic materials with biobased polymers. It further provides a strategy to cost-effectively and efficiently produce such biomaterials, and with details their significance and applications in different sectors.

2. Production of Biobased Plastics by Microorganisms Using Low-Cost Substrates

The type of substrate, which mostly includes carbon sources, provided to the microbial system is the most significant factor that wholly determines the cost and the efficiency of the entire biobased polymer production process [13]. The generation of biobased polymers is a type of defense mechanism shown by the microbe under any stress conditions. These polymers are inclusion bodies that serve as energy and carbon storage materials [14]. Other than high production costs, consumers' attitudes towards biobased materials are a significant factor. As an important element, the public needs to contribute to environmental sustainability. Although biodegradable materials are made with improved and similar properties (toughness, flexibility, etc.) to conventional plastics using additives and plasticizers, this can later lead to toxicity. These challenges have restricted the upscaling of biobased biodegradable materials in the market [15]. Some issues are addressed by replacing expensive carbon substrates with waste from different industries for microbial production of biobased plastics (Table 1). Various microbial species like *Bacillus* sp., *Rhodopseudomonas* sp., *Cupriavidus necator*, Micoralage, and mixed microbial cultures have been found to produce biopolymers like polyhydorxybutyrate (PHB), polyhydroxybutyrate-co-hydroxyvalerate (PHBV), etc. This will not only solve the problem of higher processing costs, but will help to take this concept to a larger scale, further promoting and expanding the market for such products [16]. The most essential features that make a product environmentally sustainable include its biodegradability, non-toxicity, and biocompatibility. Any compound of biobased origin manufactured from various renewable resources through microbial fermentation can fairly avoid the onset of environmental consequences that usually occur from improper disposal [17]. Table 1 provides a list of microbes and substrates for the cost-effective production of various biomaterials, thus presenting the ongoing research and development in the field of biomaterials.

Table 1. List of microbes and substrates for cost-effective biobased plastic production.

S.No.	Microbe	Substrate	Biobased Product	Product Yield	References
1.	MMC	Acid-rich waste stream	PHA	43.5% *w*/*w*	[18]
2.	*Bacillus megaterium*	VFA-rich food waste stream	PHB	9–10% CDW	[19]
3.	*Bacillus thermoamylovorans*	Waste cooking oil	[P(3HB-co-3HV)]	3.5 g/L	[20]
4.	*Halomonas hydrothermalis*	Waste frying oil	PHB	>25% CDW	[21]
5.	*Halomonas neptunia*				
6.	*Bacillus subtilis*	Fish solid waste	PHB	1.62 g/L	[22]
7.	*Haloferax mediterranei*	Food waste and levulinic acid	[P(3HB-co-3HV)]	56.70%	[23]
8.	*Bacillus wiedmannii*	Orange peel	PHB	423 mg/L	[24]
		Mango peel		390 mg/L	
		Banana peel		249 mg/L	
		Onion peel		158 mg/L	
		Rice straw		144 mg/L	

CDW; cell dry weight, MMC; mixed microbial culture, PHA; polyhydroxyalkanoate, PHB; polyhydroxybutyrate, [P(3HB-co-3HV)]; polyhydroxybutyrate-co-hydroxyvalerate, VFAs; volatile fatty acids.

There are various organizations like NatureWorks, Zero Circle, TotalEnergies Corbion, Biotec, Braskem, etc., that are using renewable resources like sugarcane, seaweed, atmospheric gases, etc., to produce biobased polymers and have also successfully established a good market.

3. Applications of Biomaterials in Different Sectors

According to European bioplastics, biobased plastics represent less than 1% of the total plastic produced annually. It has also been reported that biobased plastic production will increase from 2.18 million tons (2023) to 7.43 million tons (2028) [25]. Figure 1 provides an overview of the diversity in applicable sectors like packaging, electronics, biomedical, agriculture, textiles, construction, etc., for biobased plastics, where packaging is found to be the largest market segment [26]. However, on a smaller scale, the use of these biomaterials in different sectors will also lead to waste generation. Even though biobased plastics are environmentally sustainable and friendly, the practice of waste management is equally significant [9]. All of these materials are not degradable in the environment so approaches like chemical, mechanical, and organic recycling should be implemented.

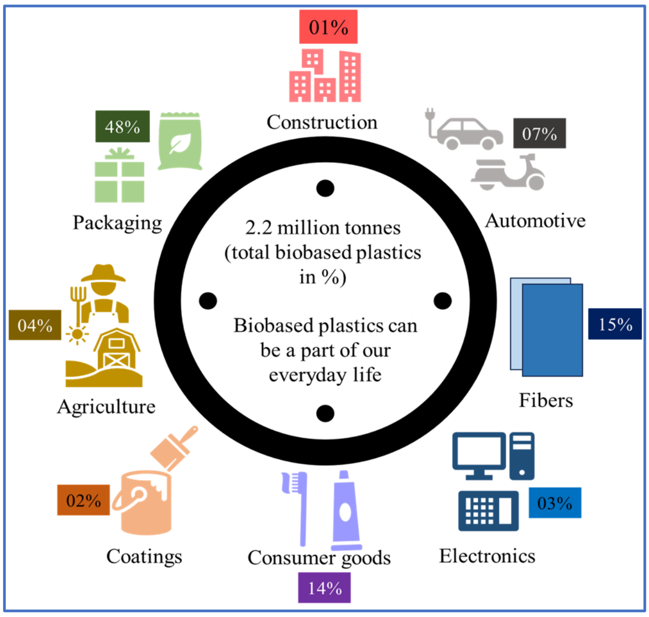

Figure 1. Different applicable sectors for biobased plastics [26].

Biobased polymers like polylactic acid (PLA) exhibit biodegradability, biocompatibility, a good mechanical strength, and a high compostability, making them a suitable substitute for conventional plastics in different sectors like packaging, agriculture, biomedicine, etc. Biobased polymers with thermal insulation are widely used in the construction industry as a (partial) replacement for concrete to achieve thermal management with respect to buildings. Other properties like high strength, non-toxicity, thermoplasticity, and improved gas barrier properties (using additives and plasticizers) make biobased polymers a suitable option in the food packaging industry. For example, composites like PLA/Lignin exhibit an improved antioxidant performance and toughness, and PLA/Selenium microparticles possess antibacterial and oxidation resistance. Biobased polymers are also widely used in the biomedical sector. Although a lower encapsulation efficiency and drug loading capacity are a few challenges faced in this case, modified formulations of PLA-based and polylactic-co-glycolic acid (PLGA) particles make the process smooth. Some biobased plastics also present good physical, chemical, biomechanical, and degradation efficiencies, making them suitable for tissue engineering [27]. The multi-functionality and environmental impact of these materials are contributing to sustainable solutions. However, with the increasing population, demand for health, energy, and food resources is also increasing. Understanding the roles of regulatory frameworks, infrastructures, and facilities in the circular economy is very important. The current linear economic approach has led to increased waste generation and resource depletion, resulting in serious environmental and public health issues. Here, the concept of a circular economy plays a role, not only in environmental, but also in industrial, socioeconomic (e.g., job creation), and ecological aspects. To strengthen the economy's backbone and grow in a sustainable manner, green technology, bio-refinery approaches, LCAs, carbon footprints, and policy play significant roles. Interdisciplinary research initiatives, consumer awareness, collaboration, and partnerships between the government, stakeholders, policymakers, and competent authorities are also required to enable circularity within ecosystems [28].

4. Conclusions

Due to the environmental impacts conventional plastics are causing, the concept of biomaterials like biobased plastics is gaining popularity. Their biobased origin, biodegradability, and biocompatibility; the reduced reliance on non-renewable resources; and fewer environmental concerns have made biobased polymers the material of choice. Although the market size of biobased plastic is still small due to high production costs, the idea of the microbial production of such polymers using cheap and easily available substrates will not only help to mitigate this problem but will also promote the circular economy approach of recovering resources from waste cost-effectively. As biobased plastics are already being used in various sectors like automotive, electronics, agriculture, etc., and are found to be sustainable, the waste generated should be properly managed. The present review tries to address the issue of plastic pollution and outlines the importance of a circular economy.

Author Contributions: J.R.: Visualization, Data curation, Formal analysis, Writing—Original draft preparation. M.S.: Conceptualization, Investigation, Writing—Original draft preparation, Writing—Review and edit, Supervision. A.K.: Data curation, Formal analysis, Writing—Original draft preparation. S.A.: Data curation, Formal analysis, Writing—Original draft preparation. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the ROYAL SOCIETY OF CHEMISTRY, UK, grant number R21-1877916181.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created.

Acknowledgments: The authors wish to acknowledge Manipal University Jaipur, India, for the motivation and support and the Royal Society of Chemistry, UK, for sanctioning the Research Fund Grant Application.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Geisendorf, S.; Pietrulla, F. The circular economy and circular economic concepts—A literature analysis and redefinition. *Thunderbird Int. Bus. Rev.* **2018**, *60*, 771–782. [CrossRef]
2. Robaina, M.; Murillo, K.; Rocha, E.; Villar, J. Circular economy in plastic waste—Efficiency analysis of European countries. *Sci. Total Environ.* **2020**, *730*, 139038. [CrossRef] [PubMed]
3. UNEP. Turning Off the Tap: How the World Can End Plastic Pollution and Create a Circular Economy | UNEP—UN Environment Programme. 2023. Available online: https://www.unep.org/resources/turning-off-tap-end-plastic-pollution-create-circular-economy (accessed on 15 June 2023).
4. Soares, J.; Miguel, I.; Venâncio, C.; Lopes, I.; Oliveira, M. Public views on plastic pollution: Knowledge, perceived impacts, and pro-environmental behaviours. *J. Hazard. Mater.* **2021**, *412*, 125227. [CrossRef] [PubMed]
5. Filho, W.L.; Salvia, A.L.; Bonoli, A.; Saari, U.A.; Voronova, V.; Klõga, M.; Kumbhar, S.S.; Olszewski, K.; De Quevedo, D.M.; Barbir, J. An assessment of attitudes towards plastics and bioplastics in Europe. *Sci. Total Environ.* **2021**, *755*, 142732. [CrossRef] [PubMed]
6. Moshood, T.D.; Nawanir, G.; Mahmud, F.; Mohamad, F.; Ahmad, M.H.; AbdulGhani, A. Sustainability of biodegradable plastics: New problem or solution to solve the global plastic pollution? *Curr. Res. Green Sustain. Chem.* **2022**, *5*, 100273. [CrossRef]
7. Abrha, H.; Cabrera, J.; Dai, Y.; Irfan, M.; Toma, A.; Jiao, S.; Liu, X. Bio-Based Plastics Production, Impact and End of Life: A Literature Review and Content Analysis. *Sustainability* **2022**, *14*, 4855. [CrossRef]
8. Bishop, G.; Styles, D.; Lens, P.N.L. Environmental performance comparison of bioplastics and petrochemical plastics: A review of life cycle assessment (LCA) methodological decisions. *Resour. Conserv. Recycl.* **2021**, *168*, 105451. [CrossRef]
9. Nandakumar, A.; Chuah, J.A.; Sudesh, K. Bioplastics: A boon or bane? *Renew. Sustain. Energy Rev.* **2021**, *147*, 111237. [CrossRef]

10. Mannina, G.; Presti, D.; Montiel-Jarillo, G.; Carrera, J.; Suárez-Ojeda, M.E. Recovery of polyhydroxyalkanoates (PHAs) from wastewater: A review. *Bioresour. Technol.* **2020**, *297*, 122478. [CrossRef]
11. Folino, A.; Karageorgiou, A.; Calabrò, P.S.; Komilis, D. Biodegradation of Wasted Bioplastics in Natural and Industrial Environments: A Review. *Sustainability* **2020**, *12*, 6030. [CrossRef]
12. Pathak, S.; Sneha, C.; Mathew, B.B. Bioplastics: Its Timeline Based Scenario & Challenges. *J. Polym. Biopolym. Phys. Chem.* **2014**, *2*, 84–90. [CrossRef]
13. Li, H.; Zhang, J.; Shen, L.; Chen, Z.; Zhang, Y.; Zhang, C.; Li, Q.; Wang, Y. Production of polyhydroxyalkanoates by activated sludge: Correlation with extracellular polymeric substances and characteristics of activated sludge. *Chem. Eng. J.* **2019**, *361*, 219–226. [CrossRef]
14. Moradali, M.F.; Rehm, B.H.A. Bacterial biopolymers: From pathogenesis to advanced materials. *Nat. Rev. Microbiol.* **2020**, *18*, 195–210. [CrossRef] [PubMed]
15. Mekonnen, T.; Mussone, P.; Khalil, H.; Bressler, D. Progress in bio-based plastics and plasticizing modifications. *J. Mater. Chem. A* **2013**, *1*, 13379–13398. [CrossRef]
16. Rajvanshi, J.; Sogani, M.; Kumar, A.; Arora, S.; Syed, Z.; Sonu, K. Science of the Total Environment Perceiving biobased plastics as an alternative and innovative solution to combat plastic pollution for a circular economy. *Sci. Total Environ.* **2023**, *874*, 162441. [CrossRef] [PubMed]
17. Thakur, S.; Chaudhary, J.; Singh, P.; Alsanie, W.F.; Grammatikos, S.A.; Thakur, V.K. Synthesis of Bio-based monomers and polymers using microbes for a sustainable bioeconomy. *Bioresour. Technol.* **2022**, *344*, 126156. [CrossRef]
18. Perez-Zabaleta, M.; Atasoy, M.; Khatami, K.; Eriksson, E.; Cetecioglu, Z. Bio-based conversion of volatile fatty acids from waste streams to polyhydroxyalkanoates using mixed microbial cultures. *Bioresour. Technol.* **2021**, *323*, 124604. [CrossRef]
19. Vu, D.H.; Wainaina, S.; Taherzadeh, M.J.; Åkesson, D.; Ferreira, J.A. Production of polyhydroxyalkanoates (PHAs) by Bacillus megaterium using food waste acidogenic fermentation-derived volatile fatty acids. *Bioengineered* **2021**, *12*, 2480–2498. [CrossRef]
20. Sangkharak, K.; Khaithongkaeo, P.; Chuaikhunupakarn, T.; Choonut, A.; Prasertsan, P. The production of polyhydroxyalkanoate from waste cooking oil and its application in biofuel production. *Biomass Convers. Biorefinery* **2021**, *11*, 1651–1664. [CrossRef]
21. Pernicova, I.; Kucera, D.; Nebesarova, J.; Kalina, M.; Novackova, I.; Koller, M.; Obruca, S. Production of polyhydroxyalkanoates on waste frying oil employing selected Halomonas strains. *Bioresour. Technol.* **2019**, *292*, 122028. [CrossRef]
22. Mohapatra, S.; Sarkar, B.; Samantaray, D.P.; Daware, A.; Maity, S.; Pattnaik, S.; Bhattacharjee, S. Bioconversion of fish solid waste into PHB using Bacillus subtilis based submerged fermentation process. *Environ. Technol.* **2017**, *38*, 3201–3208. [CrossRef] [PubMed]
23. Priya, A.; Hathi, Z.; Haque, M.A.; Kumar, S.; Kumar, A.; Singh, E.; Lin, C.S.K. Effect of levulinic acid on production of polyhydroxyalkanoates from food waste by Haloferax mediterranei. *Environ. Res.* **2022**, *214*, 114001. [CrossRef] [PubMed]
24. Danial, A.W.; Hamdy, S.M.; Alrumman, S.A.; Gad El-Rab, S.M.F.; Shoreit, A.A.M.; Hesham, A.E.L. Bioplastic production by bacillus wiedmannii as-02 ok576278 using different agricultural wastes. *Microorganisms* **2021**, *9*, 2395. [CrossRef] [PubMed]
25. Bioplastics Market Data—European Bioplastics. Available online: https://www.european-bioplastics.org/market/https://www.european-bioplastics.org/market/ (accessed on 27 December 2023).
26. Applications/Sectors—European Bioplastics e.V. Available online: https://www.european-bioplastics.org/market/applications-sectors/ (accessed on 29 July 2023).
27. Balla, E.; Daniilidis, V.; Karlioti, G.; Kalamas, T.; Stefanidou, M.; Bikiaris, N.D.; Vlachopoulos, A.; Koumentakou, I.; Bikiaris, D.N. Poly(lactic Acid): A Versatile Biobased Polymer for the Future with Multifunctional Properties—From Monomer Synthesis, Polymerization Techniques and Molecular Weight Increase to PLA Applications. *Polymers* **2021**, *13*, 1822. [CrossRef]
28. Mukherjee, P.K.; Das, B.; Bhardwaj, P.K.; Tampha, S.; Singh, H.K.; Chanu, L.D.; Sharma, N.; Devi, S.I. Socio-economic sustainability with circular economy—An alternative approach. *Sci. Total Environ.* **2023**, *904*, 166630. [CrossRef]