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Polyhydroxyalkanoates (PHAs): A Comprehensive Review of Life Cycle Assessment, Environmental Impacts, and Sustainable Development

Oviyya KR[1], *Nithyalakshmi B*[2]

[1]*M.E Environmental Engineering Student, Department of Civil Engineering, Kumaraguru College of Technology, Coimbatore-641049, Tamilnadu, India.*
[2]*Assistant Professor, Department of Civil Engineering, Kumaraguru College of Technology, Coimbatore-641049, Tamilnadu, India*

ABSTRACT

Polyhydroxyalkanoates (PHAs) are gaining attention as a sustainable alternative to conventional plastics due to their biodegradability and versatile feedstock options. This paper presents a comprehensive life cycle assessment (LCA) of PHAs, focusing on their environmental impacts across key stages, from raw material extraction to end-of-life disposal. PHAs outperform conventional plastics like polyethylene (PE) and bioplastics such as polylactic acid (PLA) in terms of biodegradability, with the ability to decompose in both aerobic and anaerobic conditions, offering a significant advantage in addressing plastic waste, especially in marine environments. However, challenges remain in their production, particularly the high energy consumption during fermentation and recovery processes. By analysing data from previous LCA studies, this paper explores the environmental trade-offs of PHAs, the role of feedstock selection, and the potential for integrating PHA production into circular economy models. Recommendations for reducing energy use and optimizing production processes are proposed to enhance the sustainability of PHAs. With further advancements in microbial engineering and renewable energy integration, PHAs have the potential to play a pivotal role in the future of sustainable plastic production.

1. Introduction

Life Cycle Assessment (LCA) is a comprehensive method used to quantify the environmental impacts of products, materials, or services throughout their entire life cycle. It encompasses all stages from the extraction of raw materials to production, distribution, use, and disposal. LCA provides a critical perspective in evaluating bioplastics by analysing their true environmental impact across multiple stages, from cradle to grave. In this context, bioplastics like Polyhydroxyalkanoates (PHAs) have emerged as a promising sustainable alternative to conventional plastics, which have been associated with significant environmental degradation, primarily due to their non-biodegradable nature.

As the global community continues to grapple with plastic pollution, bioplastics offer a way forward. The promise of bioplastics lies in their ability to reduce the dependency on fossil fuels and to alleviate some of the most pressing environmental concerns associated with plastic waste. Among the various bioplastics being explored, PHAs stand out due to their versatility, biodegradability, and ability to be synthesized from renewable feedstocks. These attributes make PHAs a vital player in the transition toward more sustainable material production and waste management systems (Winnacker, 2019).

One of the primary reasons for focusing on PHAs in this study is their biodegradability. Unlike conventional plastics such as polyethylene (PE) and polyethylene terephthalate (PET), PHAs have been shown to break down under both aerobic and anaerobic conditions. Studies have demonstrated that PHAs degrade into carbon dioxide and water in aerobic environments, while producing methane in anaerobic conditions (Samer et al., 2022). This property significantly reduces their ecological footprint and presents a strong case for their environmental benefits, especially in addressing marine and terrestrial plastic pollution.

PHAs are notable for their ability to be produced from a variety of feedstocks, including sugars, fatty acids, and industrial waste like glycerol. This versatility allows producers to move away from food-based resources, which are commonly used for bioplastics like polylactic acid (PLA). By using non-food-based feedstocks, PHAs reduce the burden on agricultural resources and contribute to a more sustainable production system (Vicente et al., 2023). This capacity for production from diverse sources provides ample opportunity for comparative LCAs, examining the impact of different feedstocks on the overall environmental outcomes (Pakalapati et al., 2018).

Although PHAs hold significant promise, there are production challenges that must be addressed. One of the major obstacles is the extraction of PHAs from bacterial cells, a process that is energy-intensive and costly. This barrier limits the scalability of PHAs as an alternative to traditional plastics. Current research is focused on finding more cost-effective recovery techniques and improving microbial engineering to enhance production efficiency (Khatami et al., 2021). These challenges, while substantial, are being met with innovative solutions that could lead to more sustainable and economically viable PHA production in the future.

The integration of biorefineries in the production of PHAs is another factor that underscores their future potential. By co-producing PHAs and biofuels, industries can maximize resource use and minimize waste, creating a more sustainable production model. This integrated approach not only helps

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2. Literature Review

Previous research on the life cycle assessment (LCA) of bioplastics has highlighted several key advantages of Polyhydroxyalkanoates (PHAs) compared to conventional plastics. Most notably, PHAs' ability to biodegrade in both aerobic and anaerobic conditions positions them as a strong alternative to persistent plastics like polyethylene (PE) and polyethylene terephthalate (PET). Studies have consistently emphasized the role of PHAs in reducing the long-term environmental impact of plastic waste, particularly in marine environments where traditional plastics accumulate and cause significant ecological damage (Winnacker, 2019).

One key study emphasized the comparative advantage of PHAs in terms of biodegradability when contrasted with other bioplastics such as polylactic acid (PLA). While PLA requires industrial composting facilities for effective degradation, PHAs have been shown to degrade naturally in a variety of environments, including soil and water, under the right conditions (Samer et al., 2022). This characteristic is crucial when evaluating the end-of-life stage of PHAs through LCA, as it directly influences their environmental performance in reducing plastic pollution.

Several LCAs have also analysed the different **feedstocks** used in the production of PHAs, and this has emerged as a critical factor in their overall sustainability. Research shows that using non-food-based feedstocks, such as waste oils, glycerol, and agricultural residues, can significantly reduce the environmental impact of PHA production. This is a major distinction from PLA, which often relies on corn-based feedstocks, leading to concerns about food security and resource allocation (Pakalapati et al., 2018). In particular, the use of waste glycerol, a byproduct of biodiesel production, has been shown to improve the LCA outcomes of PHAs by repurposing industrial waste while avoiding competition with food crops (Vicente et al., 2023).

However, despite these advantages, studies have highlighted the high energy consumption associated with the **fermentation and extraction** processes in PHA production. The energy requirements for maintaining optimal microbial growth conditions during fermentation, combined with the challenges of recovering PHAs from bacterial cells, contribute to elevated greenhouse gas emissions (Khatami et al., 2021). This represents a significant challenge when comparing PHAs to other bioplastics and conventional plastics in LCA studies. Research points to the need for technological innovations in fermentation and recovery techniques to reduce energy usage and make PHAs more competitive in terms of overall environmental performance (Nhu et al., 2024).

3. LCA Process

The life cycle assessment (LCA) process of Polyhydroxyalkanoates (PHAs) involves evaluating the environmental impacts associated with each stage, from raw material extraction to end-of-life disposal. This section will outline the key stages in the life cycle of PHAs, including raw material sourcing, production, usage, and disposal, while drawing comparisons to conventional plastics like polyethylene (PE) and bioplastics like polylactic acid (PLA).

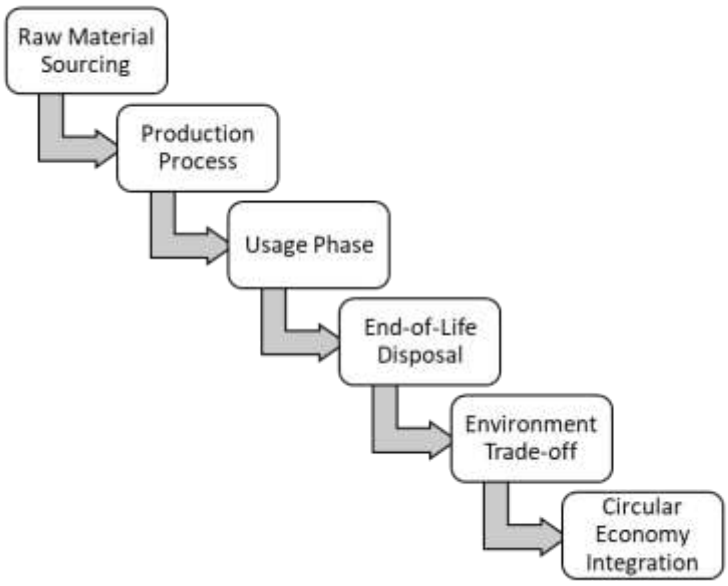

Fig.1: Flowchart of LCA process

3.1 Raw Material Sourcing

PHAs can be synthesized from a variety of feedstocks, including agricultural crops (e.g., sugarcane, corn), hydrocarbons, and industrial waste such as glycerol. The flexibility in feedstock selection offers a significant advantage over other bioplastics like PLA, which are more dependent on food-based resources (Vicente et al., 2023). The ability to use non-food-based sources such as waste glycerol, a byproduct of biodiesel production, allows PHAs to sidestep the food versus fuel debate that commonly arises with bioplastics derived from edible crops (Pakalapati et al., 2018).

Studies have shown that the environmental impact of PHA production can be significantly reduced when waste materials are used as feedstocks. For example, using agricultural residues such as sugarcane bagasse or waste oils not only minimizes waste but also improves the sustainability of the overall life cycle (Nhu et al., 2024). In contrast, conventional plastics like PE and PET are synthesized from petrochemical feedstocks, which contribute to greenhouse gas emissions and deplete non-renewable resources. The sourcing of renewable feedstocks for PHAs therefore offers a distinct advantage in reducing upstream environmental impacts (Nanda et al., 2022).

3.2 Production and Fermentation

The production of PHAs typically involves the microbial fermentation of the chosen feedstock. This process is energy-intensive, requiring specific conditions such as temperature and pH control to maximize bacterial growth and PHA accumulation. The energy demands during fermentation are a key factor that distinguishes PHAs from conventional plastics, which often have lower production energy requirements (Khatami et al., 2021). However, advancements in microbial engineering and fermentation technologies are gradually improving the efficiency of PHA production, leading to lower energy consumption and reduced emissions (Meereboer et al., 2020).

One of the main challenges in the production stage is the recovery of PHAs from bacterial cells. Current recovery methods, such as solvent extraction, are costly and contribute to the overall energy consumption of the process. Research is being conducted to explore more energy-efficient recovery techniques that could further improve the environmental performance of PHAs (Nhu et al., 2024). Despite these challenges, PHAs have the advantage of being produced from renewable feedstocks, unlike conventional plastics, which are derived from fossil fuels (Winnacker, 2019).

3.3 Use Phase

In terms of their use phase, PHAs offer performance characteristics similar to conventional plastics. They are durable and can be used in a wide range of applications, from packaging to medical devices (Rasheed et al., 2024). The use phase of PHAs is generally comparable to that of other plastics like PE and PET in terms of durability and functionality. However, what sets PHAs apart is their ability to biodegrade at the end of their life, which significantly reduces their environmental footprint (Samer et al., 2022).

3.4 End-of-Life Disposal

The most significant environmental benefit of PHAs comes at the end of their life cycle. PHAs are fully biodegradable in both aerobic and anaerobic conditions, offering a distinct advantage over conventional plastics, which typically persist in the environment for hundreds of years (Meereboer et al., 2020). Unlike PLA, which often requires industrial composting facilities for effective degradation, PHAs can biodegrade naturally in environments such as soil and marine ecosystems (Samer et al., 2022). This characteristic makes PHAs a valuable alternative in tackling the global issue of plastic waste accumulation.

Compostable PHAs contribute positively to soil health when broken down, which is a significant advantage in agricultural applications where PHAs can be used for biodegradable mulch films or other single-use items (Nhu et al., 2024). The ability to close the loop on plastic waste through composting or biodegradation is a key feature of PHAs that aligns with circular economy principles (Nanda et al., 2022).

3.5 Comparative Summary

When comparing PHAs to conventional plastics like PE and bioplastics like PLA, PHAs' biodegradability offers the most substantial environmental advantage, particularly in end-of-life scenarios. While their production process remains more energy-intensive than traditional plastic production, ongoing research into energy-efficient fermentation and recovery methods shows promise in reducing these impacts (Khatami et al., 2021). Additionally, the use of renewable, non-food-based feedstocks offers a critical advantage in terms of sustainability, particularly when compared to conventional plastics derived from petrochemicals (Pakalapati et al., 2018).

There is also a growing body of literature that examines the role of PHAs in the **circular economy**, particularly in the context of end-of-life disposal and waste management. The ability of PHAs to be composted and to contribute to soil health is a significant advantage over conventional plastics, which either persist in the environment or require energy-intensive recycling processes (Meereboer et al., 2020). Compostable PHAs offer an opportunity to close the loop on plastic waste management, particularly in agricultural applications where the degradation of PHAs can enhance soil quality while reducing the need for synthetic fertilizers (Meereboer et al., 2020).

Despite the extensive research conducted on the environmental benefits of PHAs, there are still **gaps in the literature** that need to be addressed. For instance, while there is substantial evidence supporting the biodegradability of PHAs, further research is needed to better understand their long-term degradation behavior in diverse environmental conditions, such as in marine ecosystems. Additionally, more comparative LCA studies are required to examine how different production methods, feedstocks, and geographic regions impact the overall environmental footprint of PHA production (Nanda et al., 2022). There is also limited research available on the potential of integrating PHA production with biofuel generation, a promising area that could significantly enhance the environmental performance of PHAs in a biorefinery setting (Nanda et al., 2022).

In summary, while the literature demonstrates the considerable potential of PHAs as a sustainable alternative to conventional plastics, challenges related to production efficiency, energy use, and scalability remain. Continued research in microbial engineering, feedstock diversification, and recovery techniques will be crucial in addressing these challenges and optimizing the life cycle performance of PHAs.

4. Case Study Analysis

This section provides an in-depth analysis of PHAs' life cycle assessment (LCA) data, comparing it with conventional plastics like polyethylene (PE) and other bioplastics like polylactic acid (PLA). By examining the environmental performance across key life cycle stages, we can better understand the benefits and trade-offs of using PHAs over other materials.

4.1 Production Phase Comparison

The production process for PHAs, as previously discussed, relies on microbial fermentation, an energy-intensive step in its life cycle. However, it offers significant advantages in terms of **feedstock flexibility**. For example, **Tsang et al., 2019** conducted a study comparing the environmental impacts of different feedstocks used in PHA production, such as sugars, oils, and waste materials. The study found that using waste feedstocks like glycerol or agricultural residues could significantly reduce the carbon footprint of the production process. In contrast, PLA, which is often derived from corn, faces criticism for its reliance on food crops, potentially exacerbating land use concerns and contributing to food insecurity (Tsang et al., 2019).

4.2 End-of-Life Comparisons

A key strength of PHAs lies in their superior end-of-life performance compared to conventional plastics. **Rosenboom et al., 2022** provide an in-depth analysis of the biodegradability of PHAs in natural environments, particularly in marine ecosystems. The study highlights that PHAs degrade significantly faster than PLA, which typically requires industrial composting facilities for effective decomposition. PHAs can break down in various environmental conditions, reducing the risk of plastic pollution, particularly in marine environments, where plastic accumulation is a growing concern (Rosenboom et al., 2022).

4.3 Environmental Emissions and Energy Use

While PHAs offer a clear advantage in biodegradability, their production process remains more energy-intensive than conventional plastics like PE. **Mahato et al., 2021** conducted a comparative study on energy use and greenhouse gas emissions during the production of PHAs and conventional plastics. The study found that although PHAs have higher initial energy demands during production, their overall environmental impact is mitigated by their end-of-life biodegradability. In contrast, PE persists in the environment for hundreds of years, leading to long-term ecological damage (Mahato et al., 2021).

4.4 Feedstock Sourcing and Resource Use

The choice of feedstock plays a critical role in determining the overall environmental footprint of PHA production. **Mannina & Mineo, 2024** explored the environmental benefits of using renewable feedstocks, such as sugarcane bagasse and other agricultural residues, to produce PHAs. Their study found that using non-food-based resources greatly enhances the sustainability of the production process by reducing the land and water use associated with food crops like corn or sugarcane (Mannina & Mineo, 2024). This contrasts with the sourcing of raw materials for PE production, which relies heavily on petrochemical feedstocks, further exacerbating greenhouse gas emissions (Rasheed et al., 2024).

4.5 Circular Economy and Soil Health

One of the most promising aspects of PHAs is their role in supporting a circular economy. **Mandal et al., 2024** studied the impact of compostable PHAs on soil health, particularly when used in agricultural applications like mulch films. Their research demonstrated that PHAs not only degrade completely in composting conditions but also contribute to improving soil quality by returning valuable organic matter. This provides a clear advantage over conventional plastics, which often accumulate in landfills and contribute to soil contamination (Mandal et al., 2024).

4.6 Summary of Case Study Findings

When comparing PHAs to conventional plastics like PE and other bioplastics like PLA, it becomes clear that PHAs offer substantial environmental benefits, particularly in terms of biodegradability and feedstock flexibility. While their production process requires more energy, the use of renewable and waste feedstocks, as well as their contribution to soil health and circular economy models, makes PHAs a superior alternative in the long run (Nhu et al., 2024).

5. Discussion

The case study analysis of PHAs highlights both their strengths and limitations in the context of environmental sustainability. This section will focus on critically evaluating these findings, with particular attention to their biodegradability, energy use during production, and contribution to a circular economy.

5.1 Environmental Benefits of Biodegradability

One of the most significant advantages of PHAs is their biodegradability, which far surpasses that of conventional plastics like PE and even other bioplastics like PLA. The ability of PHAs to degrade in natural environments, including marine ecosystems, addresses one of the most pressing concerns in modern waste management: plastic pollution. According to **Keith et al., 2024**, the biodegradability of PHAs in diverse environmental conditions makes them an ideal candidate for reducing long-term ecological damage caused by persistent plastics (Keith et al., 2024).

Furthermore, **Katagi et al., 2024** discuss the potential of PHAs in marine applications, where traditional plastics accumulate and cause significant harm to marine life. PHAs' ability to degrade without leaving toxic residues makes them suitable for use in products that are likely to enter marine environments, such as fishing gear or marine packaging (Katagi et al., 2024). This aspect is especially important in addressing the growing concern of microplastic pollution, as PHAs break down into harmless organic matter.

5.2 Challenges in Energy Use and Emissions

While PHAs excel in terms of biodegradability, their production process remains energy-intensive, particularly during the fermentation and recovery stages. **Gautam et al., 2024** conducted a comprehensive analysis of the greenhouse gas emissions associated with PHA production and found that while the overall emissions are lower than those of conventional plastics in the long run, the energy demands during production present a significant challenge (Gautam et al., 2024). This highlights the need for further research into energy-efficient fermentation techniques and renewable energy sources to power the production process.

Additionally, the high energy consumption of microbial fermentation places PHAs at a disadvantage when compared to other bioplastics like PLA, which require less energy during production. However, **De Donno Novelli et al., 2021** suggest that innovations in microbial engineering could potentially lower the energy requirements of PHA production. By optimizing bacterial strains for higher PHA yields and faster recovery processes, the energy footprint of PHA production could be reduced, making it more competitive with other bioplastics (De Donno Novelli et al., 2021).

5.3 Integration into Circular Economy Models

PHAs' role in a circular economy is another key benefit, particularly in the context of composting and waste management. As **Clarke et al., 2024** argue, PHAs contribute to a closed-loop system where products are designed to biodegrade and return valuable nutrients to the soil. This contrasts sharply with conventional plastics, which are difficult to recycle and often accumulate in landfills or oceans (Clarke et al., 2024). The use of PHAs in applications such as biodegradable packaging and agricultural mulch films highlights their potential to reduce plastic waste and enhance soil health.

In agricultural settings, **Andreasi Bassi et al., 2021** point out that PHAs can be used in products like mulch films, which degrade into the soil and contribute to soil quality improvement. This not only reduces plastic waste but also helps to create a more sustainable agricultural system by improving soil fertility and reducing the need for synthetic fertilizers (Andreasi Bassi et al., 2021). These applications make PHAs a valuable component of circular economy models, where materials are continuously cycled back into the environment in a beneficial way.

5.4 Future Potential and Challenges

While PHAs show great promise as a sustainable alternative to conventional plastics, there are still challenges that need to be addressed. One of the most pressing issues is the high production cost, which currently limits the widespread adoption of PHAs in the global plastics market. However, **Keith et al., 2024** emphasize that advancements in production technology, particularly in the areas of microbial engineering and energy recovery, could help to lower these costs over time (Keith et al., 2024).

Additionally, **Katagi et al., 2024** suggest that the future of PHAs lies in their integration with other bioproducts, such as biofuels. By combining PHA production with biofuel generation, industries can maximize resource use and create a more sustainable production model. This could significantly enhance the economic viability of PHAs, making them more competitive with petrochemical-based plastics (Katagi et al., 2024).

6. Conclusion

The life cycle assessment (LCA) of Polyhydroxyalkanoates (PHAs) demonstrates their significant environmental benefits, especially in terms of biodegradability and the flexibility of using renewable feedstocks like agricultural residues and waste oils. Compared to conventional plastics such as polyethylene (PE) and even other bioplastics like polylactic acid (PLA), PHAs offer superior end-of-life performance, particularly in natural environments where they can degrade without requiring industrial composting facilities (Winnacker, 2019; Rosenboom et al., 2022). However, challenges remain, particularly the high energy demands during production, which contribute to the overall environmental footprint of PHAs (Bhatia et al., 2021). Advances in microbial engineering and recovery techniques are necessary to lower these costs and reduce emissions (Albuquerque & Malafaia, 2018). With further research and development, PHAs have the potential to integrate into circular economy models, contributing to both waste reduction and soil health, making them a viable alternative for sustainable plastic production (Ali et al., 2023; Acharjee et al., 2023).

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