



Evaluating the Life Cycle Environmental Impacts of Biodegradable and Conventional Food Packaging Materials

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Abstract

Growing environmental concerns associated with the use of petroleum-based food packaging have increased interest in biodegradable food packaging. This study was designed to assess and compare the life-cycle environmental impacts of biodegradable packaging materials (PLA and PHA), and conventional petroleum-based packaging materials (PE and PET). A comparative life cycle assessment (LCA) was adopted through a cradle to grave system boundary, which included raw material extraction, manufacturing, transportation, use and end of life scenarios. Different global warming potential, water consumption, eutrophication potential, energy demand and waste generation indicators were used to assess the impacts on the environment. It was found that the biodegradable materials had smaller impacts in GWP, eutrophication potential, manufacturing energy demand, and end-of-life emissions than the conventional plastics. Nevertheless, water usage to produce agricultural feedstocks and biomass processing for biodegradable packaging was higher. The results suggest that biodegradable packaging materials can offer environmental benefits under specific packaging production and waste management conditions, however, the sustainability of these materials is dependent on regional resources, technological developments, and waste management infrastructure. The findings of this study indicate the need for thorough LCA evaluation approach to decide food packaging alternatives to achieve sustainability.

1. Introduction

The packaging of food is an integral part of today's food supply chains, serving to prevent food contamination, to preserve food quality and to reduce food losses in storage and transport. With the rapid development of global food production, urbanization and the demand for quick packaged foods, packaging materials have been consumed in great quantities, and the issues of resource depletion and environmental pollution have come into prominence (Amjad *et al.*, 2020; Noshili *et al.*, 2022; Bilal *et al.*, 2025). The functional requirements of packaging systems (mechanical

properties, barriers to oxygen and moisture, food safety, economy) must be met and the environmental impacts must be minimized throughout the packaging system life cycle. The traditional polymers derived from petroleum are still widely used for food packaging applications, especially polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET), for their low cost, light weight, durability and excellent processability. But their reliance on fossil fuels and non-biodegradable nature has led to the rise in production of greenhouse gases, waste, and long-lasting plastic pollution in terrestrial and aquatic ecosystems

(Sangroniz *et al.*, 2019; Batool *et al.*, 2022; Akram *et al.*, 2024; Park *et al.*, 2024; Batool *et al.*, 2025). The environmental impact of packaging materials can only be addressed at the end-of-pipe phase, and a more holistic approach to the life cycle is needed, from raw material extraction through manufacture, transportation, use and end-of-pipe management. This overall environmental footprint of a packaging system can then be expressed as:

$$E_{\text{total}} = E_{\text{raw}} + E_{\text{prod}} + E_{\text{transport}} + E_{\text{use}} + E_{\text{EOL}}$$

Where, E_{total} is the total environmental impact, E_{raw} is the impact that is associated with raw materials extraction, E_{prod} is the impact in the manufacturing phase, $E_{\text{transport}}$ represents the impact in the transportation phase, E_{use} represents use phase impact, and E_{EOL} represents end-of-life treatment impacts. It is important to have this life cycle perspective because improvements in one stage of the process may lead to a burden in another (Risch, 2022; Sindhu *et al.*, 2022; Bibi *et al.*, 2024; Mafe *et al.*, 2024).

Researchers and industries have been looking for alternative packaging materials that are based on renewable sources due to the environmental problems of conventional packaging materials. Polymer production, as well as the extraction and refining of fossil fuel, are very energy intensive processes, making petroleum plastics a major source of carbon emissions. Moreover, the use of mechanical recycling to help meet demand for virgin plastics has its limitations in practice due to contamination, collection inefficiencies and degradation of polymer properties for many food packaging applications (Hopewell *et al.*, 2009; Ejaz *et al.*, 2023; Akbarian-Saravi *et al.*, 2024). In view of this, biodegradable and bio-based polymers have become a viable alternative, such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), starch-based polymers, cellulose derivatives and others (Zhang *et al.*, 2026). The terminology for sustainable polymers does need to be distinguished, though. Bio-based polymers are polymer based on one or more renewable biological resources, while biodegradable polymers are polymers that can be broken down by microorganisms into natural compounds (e.g. carbon dioxide CO_2 and water in the environment under certain conditions. In the same manner, compostable materials are a particular type of biodegradable material that can break down under controlled composting conditions; degradable means that the material can break down but does not necessarily require biological processes to happen. PLA, for instance, is a bio-based polymer that can be degraded in

industrial composting systems but that is not always done in a short time in natural environments (Rosenboom *et al.*, 2022; Chen *et al.*, 2024; Qadeer *et al.*, 2025). It is therefore essential that the use of plastics be replaced by materials that can be safely degraded, and that there be scientific assessment of the impact, not the assumption that using materials that are renewable is less impactful on the environment.

While biodegradable packaging materials offer promises for reducing environmental impacts they also come with considerations of sustainability, such as the following trade-offs in agricultural production, use of resources, and waste-management needs. Production of bio-based polymers like PLA and PHA might necessitate agricultural feedstock like corn, sugarcane or any other biomass feedstock, leading to environmental challenges in land use, irrigation, fertiliser usage, and even competing with food production. Brizga *et al.* (2020) proved that bioplastics can help decrease the reliance on fossil resources, while simultaneously enhancing the environmental challenges of land and water footprints. Likewise, water usage is an important issue as the agriculture production and biomass processing can substantially affect the overall environmental effects of biodegradable materials (Garcia *et al.*, 2022; Amjad *et al.*, 2023; Yadav & Nikalje 2024). The environmental performance of a packaging material can then be assessed by means of several different indicators, such as global warming potential (GWPs), water use, eutrophication potential and cumulative energy demand. These indicators may be mathematically represented in LCA models:

$$\text{Impact} = \sum_{i=1}^n [(Flow_i \times CF_i)]$$

Where, Impact is the environmental impact category, $Flow_i$ = quantity of the i^{th} material, energy input, emission, or resource flow, and CF_i is corresponding characterization factor for that flow causing the environmental impacts. As noted in previous studies, the use of biodegradable materials could lead to lower greenhouse gas emissions and lower utilization of fossil resources, but result in higher impacts, such as water use, depending on the feedstock source and production conditions (Chen *et al.*, 2021; Tehreem *et al.*, 2024; Nguyen *et al.*, 2024; Singh *et al.*, 2024). Thus, there is a need to consider more than one impact category when evaluating the environment.

Life Cycle Assessment (LCA) is a standard, scientific method that, by considering “cradle to grave”, can compare the environmental effects of various packaging systems. As

per ISO 14040 principles, LCA has four phases, Goal and scope definition, Life-cycle inventory analysis, Life-cycle impact assessment and Interpretation (ISO, 2006). LCA can help compare different packaging materials in the packaging research field by considering energy use, emissions, resource consumption and waste-management routes. Other studies have used LCA to assess the biodegradable and conventional packaging materials, but results can be different due to various functional units and geographical boundaries, as well as the choice of databases, electricity sources, allocation methods, and end-of-life assumptions (Guinée, 2015; Hauschild *et al.*, 2022; Nadeem *et al.*, 2024). For example, when comparing packaging materials, by mass alone (kg material), it is not necessarily the same thickness, density or amount of material that would give the same level of food protection. Moreover, environmental impacts are markedly different between the two types of plastics since end-of-life scenarios for PLA and PHA are likely to be industrial composting, whereas for conventional plastics they are primarily recycling, landfilling, or incineration. Recent reviews have highlighted the need to continue to conduct consistent LCAs that consider several impact categories and realistic waste-management scenarios to better comprehend the real environmental costs and benefits of the use of biodegradable foods packaging materials in replacing traditional packaging materials (Peck *et al.*, 2023; Goel *et al.*, 2021).

With the growing environmental issues of petroleum-based food packaging and unknown sustainability of alternatives, a detailed and transparent life-cycle assessment is needed. This study addresses the question of how to make meaningful comparisons between biodegradable and conventional food packaging materials, while existing comparisons have not been easily interpreted due to the lack of consensus on key issues such as the definition of functional unit, system boundary, inventory data, method of impact assessment, and end-of-life assumption. This study is valuable because it offers a systematic environmental comparison of biodegradable food packaging materials and conventional food packaging materials to assist researchers, food packaging industries, policymakers and consumers to make sustainable choice of food packaging materials, and to acknowledge the environmental compromises. The goal of this study is the assessment of the environmental impacts of biodegradable packaging materials (PLA/PHA) and conventional petroleum-based packaging materials

(PE/PET) through the life cycle of packaging from multiple environmental indicators such as global warming potential, water use, eutrophication potential, energy demand and end-of-life impacts. This research will help overcome methodological limitations found in previous research and help to gain a better understanding of sustainable food packaging systems for evidence-based decisions in future circular economy strategies.

2. Materials and Methods

A comparative Life Cycle Assessment (LCA) was performed to compare the environmental effects of the biodegradable and conventional food packaging materials. The aim of this study was to measure and compare the environmental costs and benefits of both biodegradable (polylactic acid, PLA and polyhydroxyalkanoates, PHA) and conventional (petroleum-based) packaging materials (polyethylene, PE and polyethylene terephthalate, PET) for the entire life cycle. The LCA methodology followed the methodology ISO 14040 and ISO 14044, which outline the principles and requirements for LCA goal and scope development, LCA inventory, LCA impact assessment and LCA interpretation (International Organization for Standardization (ISO, 2006; Hauschild *et al.* 2022). This study used a cradle-to-grave system boundary that encompassed raw material extraction, feedstock production, polymer production, packaging production, transportation, use phase and end-of-life treatment. Functional equivalence between different packaging systems was achieved by choosing the functional unit as the quantity of packaging material needed to ensure the protection and preservation of 1 kg of food product over its shelf life, not just the amount of packaging material. The reference flow was the amount of PLA/PHA or PE/PET packaging needed to meet this functional requirement, considering variations in material density, thickness, mechanical properties and barrier properties. The function-based approach makes it easier to compare different packaging materials as they can have different physical properties, yet the same protection performance, requiring different masses. (Goel *et al.*, 2021; Rosenboom *et al.*, 2022).

Data on Life-cycle inventory (LCI) have been collected from scientific literature, from LCA databases from the peer-reviewed scientific literature and from industrial inventories such as ecoinvent and GaBi databases, where available. The inventory encompassed key material and energy inputs (including agricultural feedstocks for

biodegradable plastics (including corn starch and sugar-based feedstocks and microbial biomass), electricity use, thermal energy use, water use, transportation use, on-farm losses and waste streams, and waste streams generated during the manufacturing process. The geographical scope was chosen as representative global average conditions for production and the temporal scope because recent and scientifically validated LCA data were available. The Life Cycle Impact Assessment (LCIA) method based on the known midpoint indicators was used to calculate environmental impacts. The following impact categories were assessed in this study: global warming potential (GWP), water usage, eutrophication potential and cumulative energy demand. The impacts were determined using the following general relationship:

$$Impact_i = \sum_{j=1}^n (Inventory_{ij} \times Characterization Factor_{ij})$$

Where, Environmental impact category $Impact_i$, inventory flows of individual resources or emissions $Inventory_{ij}$, and characterization factors $Characterization Factor_{ij}$ convert inventory flows to environmental impact indicators. Global warming potential was presented in kg CO₂-equivalent kg CO₂-eq, consumption of water in m³, eutrophication potential in kg phosphate equivalent (kgPO₄-eq) and energy demand as MJ. To evaluate the biodegradability of these materials, PLA and PHA were considered as representative biodegradable polymers and PE and PET were used as representative conventional packaging materials, as they are commonly used packaging alternatives in food applications (Risch, 2022; Peck *et al.*, 2023).

To assess the impact of waste-management pathways on the overall environmental performance of packaging materials, end-of-life scenarios were included. The four disposal options were: landfill disposal, incineration with energy recovery, industrial composting and recycling. The recycling scenarios assumed an efficiency of recovery as well as of recycling and took into account the production of virgin materials that were to be avoided; the case of composting was evaluated only with reference to a composting under controlled industrial conditions, since biodegradable polymers like PLA are not necessarily compostable in a controlled natural environment. The incineration scenarios incorporated assumptions on combustion emissions and potential energy recovery credits, and the landfill scenarios considered the degradation behavior, potential methane generation and landfill management practices. LCA results are quite sensitive to

various methodological considerations and regional infrastructures, so sensitivity and uncertainty analyses were performed to assess robustness. The various parameters that were analyzed were: Transportation distance, Electricity generation mix, Feedstock source, Packaging mass, Recycling rate, Composting availability, and end-of-life allocation assumptions. The effect of these parameters was evaluated by conducting scenario analysis to determine which aspects of the parameters have the greatest influence on environmental variability. This makes it easier to compare the biodegradable packaging system and the conventional packaging system in a transparent way and to facilitate the evidence-based decision making of sustainable packaging in food packaging applications (Brizga *et al.*, 2020; Hobbs *et al.*, 2021; Panou & Karabagias, 2023).

3. Results and Discussion

The comparison of life cycle assessment between biodegradable packaging materials (PLA/PHA) and the conventional packaging materials that are produced from the petroleum-based raw materials showed differences in raw material requirements, energy consumption, resource use, environmental emissions, and end-of-life performance. The results were computed through the selected LCA framework and analyzed using midpoint environmental indicators such as Global Warming Potential (GWP), Water Use, Freshwater eutrophication potential, Cumulative energy demand and Waste management impacts. The results show that the use of biodegradable packaging material can offer environmental benefits across some impact categories but can also have advantages and disadvantages relating to resource use, such as water demand.

The results of the life-cycle inventory of the biodegradable and conventional packaging materials are displayed in Table 1. The carbon emissions for the raw material extraction stage were slightly higher for biodegradable packaging (0.12 kg CO₂-eq/kg) than for conventional packaging (0.08 kg CO₂-eq/kg). The difference relates to the agriculture feedstock production needed to manufacture biodegradable polymers including cultivation, biomass processing and related energy usage. Conventional plastics, on the other hand, use petroleum as a feedstock, but have very well-developed industrial production systems.

The manufacturing stage had a lower energy demand for biodegradable packaging (1.2 MJ/kg) than for conventional packaging (1.6 MJ/kg). Likewise, the energy demand needed for transportation was slightly lower for

Table 1. Life Cycle Inventory (LCI) of biodegradable and conventional packaging materials

Life Cycle Inventory Parameter	Biodegradable Packaging (PLA/PHA)	Conventional Packaging (PE/PET)
Raw material extraction emissions	0.12 kg CO ₂ -eq/kg	0.08 kg CO ₂ -eq/kg
Manufacturing energy demand	1.2 MJ/kg	1.6 MJ/kg
Transportation energy demand	0.5 MJ/kg	0.6 MJ/kg
Water consumption	10 L/kg	5 L/kg
Manufacturing waste generation	0.05 kg waste/kg	0.10 kg waste/kg

The inventory values are summarized in life cycle inputs and emissions based on secondary LCA data and published

biodegradable materials compared to PE/PET packaging (0.5 MJ/kg/PE/PET). Biodegradable packaging materials, however, showed a higher water consumption (10 L/kg) than conventional packaging (5 L/kg); primarily because of the needs for agricultural cultivation and biomass processing. Waste created in the manufacturing process was lower with the biodegradable materials (0.05 kg/kg), which is about half the waste created during the manufacturing process with the conventional packaging (0.10 kg/kg). The global warming potentials results are given in Table 2. PLA and PHA had smaller climate change impacts than conventional polymer made from petroleum. PLA had the lowest GWP value of 1.20 kg CO₂-eq/kg and PHA had a GWP value of 1.50 kg CO₂-eq/kg. The PE and PET had higher values at 2.50 kg CO₂-eq/kg and 2.80 kg CO₂-eq/kg respectively. Partial substitution of fossil resources with renewable biomass feedstocks and variations in polymer production pathways can be correlated to the lower GWP of biodegradable polymers. The carbon advantages of biodegradable materials, however, rely heavily on the land use, kind of energy used and agricultural methods. The water consumed by the packaging materials is listed in table 2. High water inputs were needed for biodegradable materials as opposed to conventional plastics. The highest water demand occurred for PLA followed by PHA (12 and 8 L/kg, respectively), PE (4 L/kg), and PET (6 L/kg). Biodegradability, which is linked to a higher water footprint, is related to biomass cultivation, irrigation needs and agricultural processing. The results show that in certain categories, biodegradable packaging is beneficial for the environment, while in other categories, it can lead to increased water stress, especially in water-scarce areas. The results of the freshwater eutrophication potential are given in Table 2. In terms of eutrophication impacts, biodegradable materials had lower impacts than conventional plastics. The values of PLA and PHA were 0.020 kg PO₄³⁻-eq/kg and 0.010 kg PO₄³⁻-eq/kg,

respectively, while those of PE and PET were higher, 0.050 kg PO₄³⁻-eq/kg and 0.040 kg PO₄³⁻-eq/kg, respectively. The lower eutrophication potential of biodegradable materials may be due to lower fossil-based processing emissions, but the nutrient inputs to aquatic systems from the agriculture sector must be carefully monitored as over-fertilizing could lead to high nutrient losses. Tables 2 show the comparative energy consumption of the manufacturing sector in both the base and current periods. PLA and PHA had to use less production energy (1.80 MJ/kg and 1.90 MJ/kg respectively) than PE and PET (2.50 MJ/kg and 2.80 MJ/kg respectively). This lowered energy demand of biodegradable polymers can be due to the differences in the production pathways, and due to a decreased demand for energy intensive processes such as petroleum extraction and the refining process. But the whole life cycle energy performance will be affected by upstream agricultural activities and transport needs. Figure 1 shows that the different end-of-life pathways have different environmental emissions. The emissions were lower, for the different disposal scenarios evaluated, for biodegradable packaging. The incineration of PLA/PHA gave 0.80 kg CO₂-eq/kg while PE/PET had 1.50 kg CO₂-eq/kg. There was a reduction in impacts for biodegradable packaging (0.10 kg CO₂-eq/kg) compared to conventional plastics (0.50 kg CO₂-eq/kg) for recycling. The lowest impact for biodegradable materials was observed for industrial composting (0.05 kg CO₂-eq/kg), but this is only possible when a suitable composting solution is available. Biodegradable materials (0.30 kg CO₂-eq/kg) had slightly lower emissions from the landfill than conventional plastics (0.40 kg CO₂-eq/kg). The results show that end-of-life management has a significant impact on the environmental performance of packaging products. Sensitivity analysis showed that assumptions made in the system had a significant impact on environmental results. The following parameters were determined to be significant

Table 2. Global warming potential, water consumption, freshwater eutrophication potential and manufacturing energy demand of packaging materials

Packaging Material	Global Warming Potential (kg CO ₂ -eq/kg)	Water Consumption (L/kg)	Freshwater Eutrophication Potential (kg PO ₄ ³⁻ -eq/kg)	Manufacturing Energy Demand (MJ/kg)
PLA	1.20±0.05 ^d	12±0.12 ^a	0.020±0.002 ^c	1.80±0.02 ^d
PHA	1.50±0.03 ^c	8±0.09 ^b	0.010±0.001 ^d	1.90±0.01 ^c
PE	2.50±0.02 ^b	4±0.13 ^d	0.050±0.001 ^a	2.50±0.04 ^b
PET	2.80±0.04 ^a	6±0.11 ^c	0.040±0.003 ^b	2.80±0.01 ^a

Values are calculated based on midpoint climate-change characterization factors in line with LCA impact assessment framework.

factors affecting the performance of packaging materials in comparison: electricity source, origin of feedstock, efficiency of recycling, and infrastructure for wastes. The adoption of renewable energy led to reduced GHGs and better composting facilities led to better environmental value of biodegradable packaging. On the other hand, increased water requirements and agricultural effects were still significant restrictions for bio-based polymers.

Comparative life cycle assessment illustrates that there are environmental trade-offs of using biodegradable and conventional food packaging materials rather than a straightforward option of using one material in place of the other. The results have shown that biodegradable polymers like PLA and PHA can offer benefits in certain environmental impact categories as they partially rely on renewable feedstocks and are less dependent on fossil resources, which are present. The results showed that the use of biodegradable polymers, such as PLA and PHA, can have benefits in specific environmental impact categories, due to their partial dependence on renewable feedstocks and reduced dependency on fossil resources. But these advantages rely greatly on the production trail, farming methods, energy sources, and waste disposal systems. The

focus of previous work has been on the fact that the environmental performance of bioplastics cannot only be judged on their biological origin, as the life-cycle profile of the bioplastics may be influenced by upstream processes like cultivation of biomass, processing requirements and changes in land-use (Brizga *et al.*, 2020; Rosenboom *et al.*, 2022). Thus, the outcomes of this study indicate that there is a need for a multi-indicator approach to selecting sustainable packaging instead of just using an environmental indicator.

The main reason for the lower GH emissions from biodegradable packaging compared to conventional packaging is due to the different feedstocks and polymer manufacturing processes. Conventional polymers, like PE and PET, use fossil-based raw materials, sourced from crude oil and natural gas, which are used to extract, process and polymerize, accounting for a large share of the carbon emissions. Biodegradable polymers can, on the other hand, include renewable carbon sources that can minimize usage of fossil resources in the polymer production process. This is in line with the lower climate-change impacts that bio-based polymers showed than the petroleum-based ones in certain production scenarios reported in previous life-cycle

Table 3. Sensitivity analysis of the key parameters which are shown to affect the environmental performance.

Parameter Changed	Scenario	Effect on Comparative Results
Electricity source	Renewable electricity instead of fossil-based electricity	Reduced GWP for both materials, with greater reduction in polymer production stages
Transportation distance	±50% variation	Increased impacts proportionally; heavier packaging systems showed higher sensitivity
Packaging mass	±20% variation	Reduced packaging mass decreased all environmental impacts
Recycling rate	30–70% variation	Higher recycling rates reduced impacts of PE/PET systems
Composting availability	Industrial composting available/unavailable	Strong influence on biodegradable packaging benefits
Feedstock origin	Agricultural vs. waste biomass	Waste-based feedstock reduced land and water impacts

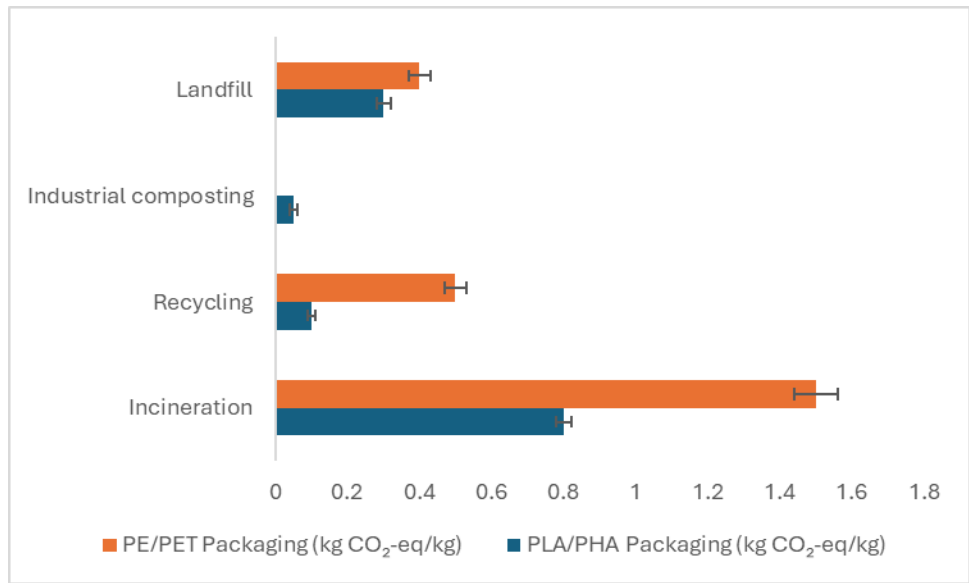


Figure 1. End-of-Life environmental impacts (Composting scenario refers to the biodegradable packaging that is composted under controlled industrial composting conditions)

studies (Chen *et al.*, 2021; Nguyen *et al.*, 2024). Bioplastics, however, do not necessarily have a carbon benefit as the agricultural process could involve using fertilisers, using land, and processing the biomass, which can also result in carbon emissions. So, the choice of low impact feedstock and renewable energy sources is still very important to enhance the environmental performance of biodegradable packaging.

The increased water use seen for biodegradable packaging is an important environmental compromise. Biodegradable polymers can rely on agricultural feedstocks which are irrigated and require cultivation input and processing water, which is not the case for conventional plastics. Previous research has identified that there is a risk of the use of first-generation crops like sugarcane and corn for bioplastics yielding negative impacts on fossil carbon emissions and positive impacts on freshwater resources (Brizga *et al.*, 2020; Harrison *et al.*, 2022). Therefore, the sustainability of the biodegradable packaging can differ significantly from one region to another due to local water resources, farming systems and choices of raw materials used. These water-related impacts could be mitigated in the future packaging system using agricultural residues, waste biomass and advanced biopolymer production technologies.

The energy performance of the materials used in biodegradable products also highlights that it is necessary to

consider the whole life cycle instead of each individual processing stage. The energy efficiency of the manufacturing of PLA and PHA, as compared to PE and PET, could be due to their reduced reliance on energy-intensive processes of extraction and refining of fossil fuels. Similar research was carried out by Nguyen *et al.* (2024), which also concluded that energy demand is one of the key factors affecting the environmental performance of other polymers. Lower manufacturing energy, however, does not necessarily mean lower total environmental impacts as there may be other negative impacts from upstream agricultural processes, transportation demands and processing conditions. Hence, future efforts need to be directed towards establishing production with high efficiency, incorporating renewable energy resources and streamlining supply chain management of biodegradable polymers.

End-of-life management is the key factor in the packaging materials final environmental performances. The outcomes suggest that in the right composting and waste management scenarios, biodegradable packaging can manage to have lower emissions. But it is not to be understood that any disposals automatically mean degradation of the environment. For instance, PLA is typically degraded under industrial compost conditions that are carefully controlled and have a well-balanced microflora, a low moisture content and temperature. Uncontrolled disposals can be less

degradative. The insufficient waste management facilities can limit the environmental benefits that can be obtained from using biodegradable materials, as highlighted in previous studies (Hobbs *et al.*, 2021; Fang & Wang, 2024). Likewise, enhancements to the recycling infrastructure of conventional plastics can help to lower their environmental impact as less virgin polymer will be needed. Hence, packaging sustainability is not only related to the material that is used but also to the waste management systems available and their performance in the region.

The results also underscore the need to take consumer attitudes and behaviors, policy, and infrastructure development into account in sustainable packaging transitions. The actual performance of packaging materials is heavily affected by consumer knowledge of disposal guidelines, whether or not industrial composting is available and recycling. The connection between technological development and human action has been shown in the past to influence the sustainability outcomes, specifically related to waste separation and disposal (López & Martínez, 2024). Thus, packaging strategy needs to combine material innovation, with policies and programs in waste management and public awareness.

Continued development of the biodegradable packaging industry will need to be directed towards the further development of the feedstocks, the more efficient production technologies and waste management systems. More focus on second generation biomass resources, on residues and waste polymer to decrease the competition with food production and the impacts on land and water. Furthermore, enhancing the industrial composting infrastructure, recycling technologies and circular material systems are needed to ensure that the benefits of biodegradable packaging are maximised. Furthermore, future LCA studies should consider the broader sustainability aspects of packaging alternatives, such as economic feasibility, social acceptance, and potential policy impacts, to offer a comprehensive evaluation of those alternatives (Wang *et al.*, 2025). The use of uncertainty analysis, regional datasets and dynamic LCA models will further enhance the reliability of environmental comparisons.

The limitations of this study should be considered when interpreting the results. Firstly, the assessment was largely performed with second-hand LCA data sources and from published literature or existing data bases, meaning that

uncertainties in the data used for the assessment can affect the reported impacts, related to the choice of data source, geographical assumptions, and methodological choices. Second, packaging systems were assessed with representative material types; the actual packaging performance will depend on the specific product requirements like barrier properties, thickness, protection of the shelf-life, mechanical strength, etc. Thirdly, not all the variations in electricity production, transport distances, agriculture, recycling facilities and compost availability were captured in the region. In addition, this research was primarily based on environmental indicators and did not consider economic costs, consumer acceptance or social sustainability issues. Further research is needed to include region specific primary data and wider sustainability indicators, for conclusions to be more widely applicable.

Conclusion

This study shows that selected life-cycle impact categories for biodegradable packaging materials (PLA and PHA) can offer environmental benefits over conventional packaging materials (PE and PET), especially in the areas of greenhouse gas emissions and eutrophication potential, energy demand and in some end-of-life scenarios. There are however trade-offs to these benefits, particularly the fact that the use of agricultural feedstock necessitates the use of a water resource, and the need for suitable waste management infrastructure. However, biodegradability is not the only factor that determines the environmental performance of biodegradable packaging; the other factors to consider are the source of the raw materials, the packaging production methods, the transportation infrastructure and waste disposal. When used in combination with other packaging solutions that follow a circular economy, biodegradable packaging could help to achieve more sustainable food packaging systems but can't be seen as a blanket solution for plastics packaging.

Author Contributions

Conceptualization: Aamna Soomro; Methodology: Rabia Rasheed Data analysis: Sadia Amjad; Writing—original draft preparation: Lubna Soomro; Writing—review and editing: Waqar Ahmad. The final manuscript has been read and approved by all the authors.

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Conflict of Interest

The authors declare that there is no conflict of interest.

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