

ASSESSING THE FEASIBILITY OF BIODEGRADABLE DIAPER ALTERNATIVES FOR SUSTAINABLE WASTE MANAGEMENT

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Declaration of Independent Work

DECLARATION WITH REGARD TO INDEPENDENT WORK

I, VINTIA MULUNGO, identity number _____ and student number _____, do hereby declare that this research project submitted to the Central University of Technology, Free State for the Master of Health Sciences in Environmental Health, is my own independent work; and complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of the Central University of Technology, Free State; and has not been submitted before to any institution by myself or any other person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

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26 September 2025

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I would like to express my sincere gratitude to everyone who has contributed to the successful completion of this study.

To God, who has been my strength since the first day of my study. I have had doubts and questioned my ability a million times. However, Your Word has always assured me that I can do anything through You who gives me strength.

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Abstract

The growing environmental burden of plastic waste has become a global concern, particularly in low- and middle-income countries, where inadequate waste collection systems contribute to uncontrolled dumping. A significant proportion of household waste in these regions consists of disposable diapers, which are composed of non-biodegradable polymers such as low-density polyethylene (LDPE), especially in the backsheet layer. These plastics can persist in landfills for over 500 years, raising urgent concerns around long-term environmental sustainability. Despite increasing awareness, there remains a critical gap in identifying and validating biodegradable polymer alternatives that can maintain product functionality while reducing ecological impact.

This dissertation aims to investigate and evaluate polylactic acid (PLA) as a viable biodegradable substitute for LDPE in disposable diaper backsheets. The study comprises two components: a literature-based review (Article 1) that assesses commercially available biodegradable polymers for diaper applications, and an experimental investigation (Article 2) that characterises the backsheets of three commercial diapers and compares their thermal, morphological and biodegradation behaviour to that of PLA.

In the review, PLA emerged as the most promising candidate due to its commercial availability, cost-effectiveness, and favourable processing characteristics relative to other biodegradable polymers such as polyhydroxyalkanoates and polybutylene succinate. However, its brittleness limits its direct use in flexible films such as diaper backsheets. The literature highlights modification strategies, including blending, plasticisation, and reinforcement, to enhance the 'mechanical properties of PLA.

The experimental study employed differential scanning calorimetry, thermogravimetric analysis, Fourier transform infrared spectroscopy, scanning electron, and soil burial biodegradation testing. Diaper C, which contained cellulose-infused PE, showed altered thermal and surface properties compared to conventional LDPE backsheets but did not significantly improve biodegradability. The cellulose degraded early during composting, while the polyethylene matrix remained intact. In contrast, PLA demonstrated lower decomposition temperatures and gradual biodegradation over time, confirming its classification as a compostable polymer.

The combined findings underscore that partial material substitution, for example, adding cellulose to LDPE, is insufficient to address the environmental impact of diaper waste. PLA-based backsheets offer a more effective alternative, with the potential to reduce long-term waste accumulation. However, successful implementation will require material innovations, supportive policy frameworks, and increased consumer and industry engagement, especially in low- and middle-income countries where waste management infrastructure is limited.

This dissertation contributes valuable knowledge toward the development and adoption of biodegradable diaper materials and lays the foundation for future research on improving the performance of sustainable polymers in hygiene applications.

Keywords: Disposable diapers, Environmental impacts, Biodegradable polymers, Sustainable alternatives, Waste management, Characterisation techniques, Polylactic acid, Low-density polyethylene

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List of Abbreviations and Symbols

°C	Degrees Celsius
%	Percentage
cm	Centimetre
cm ⁻¹	Reciprocal centimetre
g	Gram
kPa	Kilopascal
kV	Kilovolt
mg	Milligram
mm	Millimetre
wt%	Weight percentage
ASTM	American Society for Testing and Materials
C=O	Carbonyl group
DSC	Differential scanning calorimetry
DTG	Derivative thermogravimetric
FTIR	Fourier transform infrared
LDPE	Low-density polyethylene
LMICs	Low- and middle-income countries
O–H	Hydroxyl groups
PBAT	Polybutylene adipate-co-terephthalate
PBS	Polybutylene succinate
PE	Polyethylene
PHAS	Polyhydroxyalkanoates
PLA	Polylactic acid
PP	Polypropylene
SAP	Superabsorbent polymer
SDGs	Sustainable development goals
SEM	Scanning electron microscopy
TGA	Thermogravimetric analysis

Chapter 1

Introduction

1.1 Background and context

The worldwide increase in disposable diaper usage has resulted in a significant environmental issue, especially in rapid urbanising areas where waste production exceeds the capabilities of waste-management systems. Disposable diapers are engineered to enhance the receipt, absorption, and retention of infants' pee and faeces, while ensuring the comfort of the baby, maintaining skin hygiene, and facilitating carer convenience (Mendoza et al., 2019). However, they also represent a significant source of waste and environmental impacts as they are commonly made from synthetic, non-biodegradable materials such as polyethylene, polypropylene, and sodium polyacrylate superabsorbent material (Ntekpe et al., 2020; Li et al., 2024). Both developed and developing countries rely on disposable diapers rather than reusable cloth diapers (Meseldzija et al., 2013). Additionally, disposable diapers are the third-largest single-consumer item in landfills, consisting of about 4% solid waste because of their single-use nature (Ntekpe et al., 2020).

Modern diapers are made of polymers, such as polyethylene (PE), which provide a micropore barrier. The pores are too small for water droplets to pass through, but they do allow evaporation. Consequently, the outside air has lower relative humidity and is drier (Dey et al., 2016). Though effective in keeping moisture inside, PE contributes significantly to long-term waste accumulation as it does not degrade naturally. The need to replace conventional plastics with biopolymers is urgent. This is because of the high energy demands of plastic processing and the carbon emissions it generates, further polluting the environment. It is essential to identify sustainable alternatives to mitigate these impacts and address the growing environmental challenges. Moreover, the absence of empirical data comparing biodegradable alternatives to conventional diapers regarding degradation characteristics, economic considerations, absorbency, degradation characteristics, and structural integrity constitutes a significant vacuum for waste management and stakeholders policymakers. Thus, it is crucial to evaluate the viability of biodegradable nappies as practical, sustainable alternatives within current waste-management systems.

This study explores the use of biodegradable polymers as a sustainable replacement for PE in disposable diapers. It focuses on reducing waste accumulation and minimising environmental pollution. Promoting biodegradable alternatives could lead to faster decomposition and contribute to a healthier environment, especially as the issue of diaper waste grows in scale. Addressing diaper waste is important, as improper disposal methods, such as burning, burying, or illegal dumping pollute public spaces, farmland, and natural landscapes (Ntekpe et al., 2020). Recent studies offer promising interventions; for instance, Ferroanto et al. (2020) examined vermicomposting which used diapers, while Mandoza et al. (2019) demonstrated that glue-free diaper designs can reduce manufacturing costs. However, there are still gaps in the search for fully biodegradable solutions for the PE layer, which is a key contributor to waste persistence. This study was important because it sought to fill the existing gaps in the literature by assessing biodegradable polymers to promote environmental health and sustainable waste management.

1.2 Research aim and objectives

The main aim of this study was to explore the feasibility of implementing biodegradable diaper alternatives as a sustainable solution for managing disposable diaper waste. The study specifically focused on evaluating the biodegradability and material performance of polylactic acid (PLA) in comparison with PE, which is commonly used in conventional disposable diaper backsheets. The ultimate goal was to contribute to environmental pollution reduction and support public health through innovative, eco-friendly material solutions.

The specific objectives were:

1. **To evaluate the thermal properties** of the diaper backsheets using differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA).
2. **To characterise the chemical composition** of commercial diaper backsheets using Fourier transform infrared (FTIR) spectroscopy and compare it with LDPE and PLA reference materials.
3. **To assess morphological changes** on the surface of diaper backsheets using scanning electron microscopy.

4. **To determine the biodegradability** of the diaper backsheets in an organic compost environment following the method of the American Society for Testing and Materials (ASTM D6003-96), by monitoring weight loss and physical degradation over time.
5. **To compare the degradation behaviour** of diaper backsheets with that of LDPE (a conventional plastic) and PLA (a known biodegradable polymer), under identical composting conditions.

1.3 Structure of the dissertation

- **Chapter 1: Introduction** – Provides the background and context of the study. It also includes the problem statement; research aims and objectives. Furthermore, it outlines the scope and structure of the dissertation.
- **Chapter 2: Literature review** – This chapter reviews existing literature on disposable diapers and their environmental impacts. It also focuses on the use of biodegradable polymers such as PLA in waste management. Lastly, it discusses degradation mechanisms, polymer characterisation techniques, and gaps in the literature.
- **Chapter 3: Methodology** – Describes the materials, sample preparation, experimental design, and analytical techniques used such as DSC, TGA, FTIR, and SEM.
- **Chapter 4: Results and discussion** – Present the findings and interprets them in the context of existing literature.
- **Chapter 5: Conclusions**– Summarises the key contributions, implications, and areas for future research.

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Chapter 2

Literature review

This chapter has been published under the title:

Feasibility and Implications of Biodegradable Diaper Alternatives

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Abstract

Disposable diapers contribute significantly to municipal solid waste, with non-biodegradable polymers such as low-density polyethylene (LDPE) persisting in landfills for centuries. Biodegradable alternatives, including polylactic acid (PLA), poly(butylene adipate-co-terephthalate) (PBAT), bamboo, and organic cotton, offer reduced environmental persistence, although challenges remain regarding cost, mechanical performance, and scalability. This review synthesizes current literature on these materials, highlighting their properties, biodegradation mechanisms, environmental performance, and commercial feasibility. In addition, we examine emerging biodegradable superabsorbent polymers (SAPs), such as polysaccharide-based hydrogels, chitosan, and nanocellulose, essential for fully compostable diapers. Our review uniquely integrates material performance, tropical high-humidity degradation, cost considerations, and consumer acceptance, providing insights into both technological advances and barriers to adoption. Key challenges include high production costs, supply chain limitations, and maintaining performance parity with conventional diapers. Finally, we discuss sustainable waste management strategies, including industrial composting, and identify future research directions focused on optimizing biopolymer properties, safety, and life-cycle impacts. This synthesis informs researchers, industry stakeholders, and policymakers seeking to advance environmentally responsible diaper products.

Keywords: disposable diapers; low-density polyethylene; biodegradable polymers; polylactic acid; poly(butylene adipate-co-terephthalate); bamboo fibre; organic cotton; sustainable waste management; superabsorbent polymers; biodegradable hydrogels; nanocellulose

2.1 Introduction

Disposable diapers are commonly made from synthetic, non-biodegradable materials that contain absorbent chemicals to manage urination or excrement (Ntekpe et al., 2020). The rising demand for disposable diapers, especially in urban settings, has caused significant waste management challenges and environmental concerns. A newborn typically needs about 5000 diaper changes before potty training, with disposable diapers accounting for about 95% of these changes. Both high-income and low- and middle-income countries depend heavily on disposable rather than reusable cloth diapers (Meseldzija et al., 2013). Globally, disposable diapers contribute ~4% of municipal solid waste, as presented in Figure 2.1, and require centuries to decompose (Ntekpe et al., 2020). In low-income countries, poor disposal infrastructure leads to open dumping, burning, and sewage blockages (Kimani et al., 2015; Płotka-Wasyłka et al., 2022) worsening public health risks. Conventional disposable diapers present a significant environmental and public health challenge, particularly in regions with limited waste management infrastructure (Kordecki et al., 2022; Shah et al., 2024). Collectively, studies from Europe, Asia, and Africa demonstrate that conventional disposable diapers present both environmental and public health challenges, particularly in regions lacking effective waste management infrastructure (Iskandar et al., 2025).

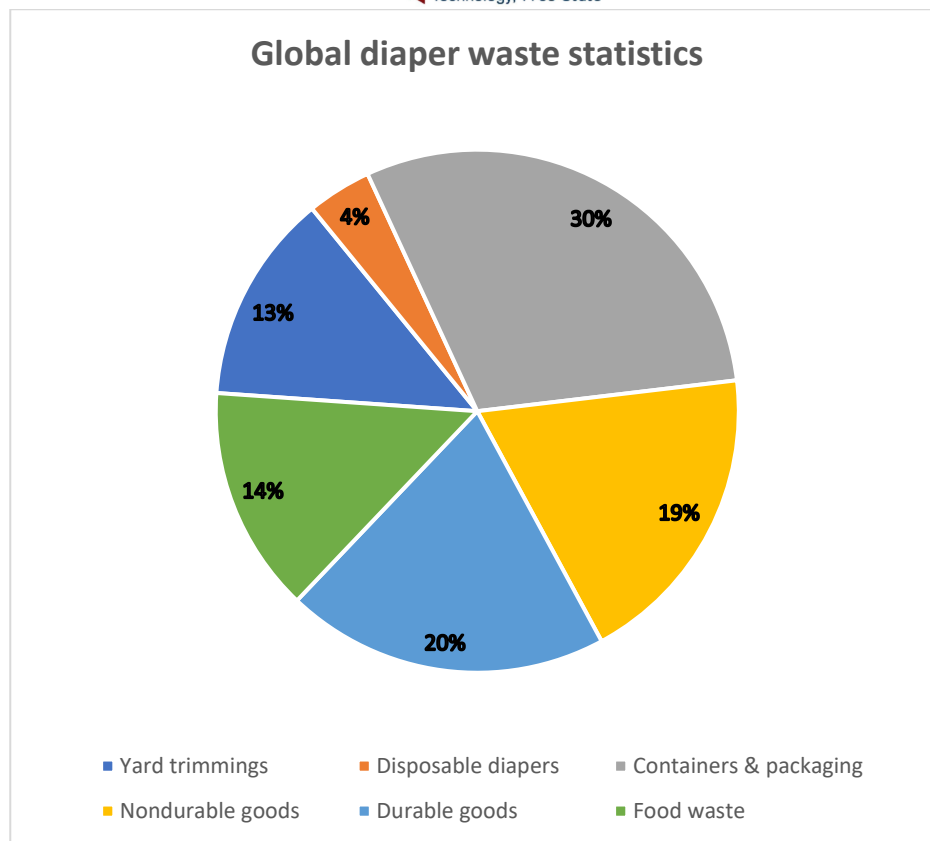


Figure 2.1. Global diaper waste statistics. (Source: Data adapted from Ndifreke et al., 2020) [open access].

Common parental disposal methods in African countries include open dumping, burial, incineration, or flushing down toilets, reflecting limited awareness of health hazards (Jesca and Junior, 2015). Incineration can reduce waste volume but often produces air pollutants and is costly; open burning and shallow burial are common due to poor regulatory compliance (Kimani et al., 2015; Płotka-Wasyłka, 2022). Open burning releases dioxins, furans, and particulate matter, while landfilling introduces chemical leachates into soil and groundwater (Zhang et al., 2017).

Modern diapers are mainly composed of polymers, such as low-density polyethylene (LDPE), which provide a moisture barrier but are persistent in the environment. While conventional diapers persist for centuries, biodegradable alternatives can degrade within months under appropriate conditions, highlighting their potential for sustainable waste management (Iskandar et al., 2025). Biopolymer-based diapers, including PLA and PBAT, have received

increasing attention for their potential to replace LDPE while reducing environmental impact (Fu et al., 2020). However, successful adoption requires balancing environmental benefits with consumer acceptance, cost, and regulatory compliance.

In addition to the polyolefin outer layers, a critical barrier to fully biodegradable diapers lies in the superabsorbent polymer (SAP), which is conventionally sodium polyacrylate. This polymer provides excellent liquid uptake and retention but is essentially non-biodegradable, thereby contributing significantly to persistent waste and microplastic concerns (Gadtya et al., 2023). Several biodegradable substitutes have been explored in recent years. Polysaccharide-based hydrogels—for example, carboxymethyl cellulose or starch derivatives—can be chemically modified via graft copolymerization or crosslinking to enhance swelling while retaining biodegradability (e.g., in starch–polyacrylic acid systems) (Czarnecka, E. and Nowaczyk, 2020). Composite systems combining alginate and starch have also been demonstrated as biodegradable SAP beads with acceptable absorption behaviour under experimental conditions (Lertsarawut et al., 2024).

This review examines biodegradable diaper alternatives, emphasizing their composition, mechanical performance, biodegradability, economic feasibility, and sustainability implications. Additionally, it highlights consumer acceptance, challenges to adoption, policy considerations, and future research directions, providing insights into the implementation of more sustainable waste management practices in low- and middle-income countries. Unlike prior reviews that primarily focused on biodegradable outer-layer materials, it comprehensively examines both outer layers and emerging biodegradable SAPs, while considering material performance, cost, and degradation under tropical, high-humidity conditions. This integrated perspective highlights both technological advances and practical challenges in implementing fully biodegradable diapers. It argues that true adoption of biodegradable diapers depends on material innovations and also on solving the interlinked challenges of cost, SAP performance, and the establishment of biodegradable waste infrastructure.

This review provides an overview of disposable diapers, highlighting their composition, widespread use, and environmental impacts, especially in low- and middle-income countries. It then provides a comprehensive review of biodegradable alternatives, including key materials such as PLA, PBAT, bamboo, and organic cotton, along with their characteristics, manufacturing processes, and biodegradability mechanisms. The discussion further evaluates performance, safety, and consumer acceptance of biodegradable diapers, with emphasis on absorbency, comfort, and health considerations. The subsequent sections examine challenges and barriers to adoption, focusing on cost, scalability, and product consistency. The review further identifies future research priorities, particularly in material innovation, safety testing, and understanding biodegradation pathways under real-world conditions. Finally, the paper concludes with a synthesis of findings and proposes research priorities and strategies needed to enable the widespread adoption of biodegradable diaper technologies.

2.2 Conventional Diapers and Their Environmental Impact

2.2.1 Composition and Materials Used in Conventional Diapers

A disposable diaper typically consists of four main layers: the top sheet, acquisition layer, absorbent core, and backsheet (Figure 2.2). The top sheet is a soft, porous polypropylene layer that rapidly transfers moisture to the inner layers and may include a lotion to protect the skin. The acquisition layer traditionally contains SAPs, which are non-biodegradable. The (Li et al., 2024) acquisition layer distributes liquid evenly to the absorbent core, which acts as the main SAP reservoir. Recent developments have introduced plant-derived cellulose into this layer, improving biodegradability without compromising absorbency.

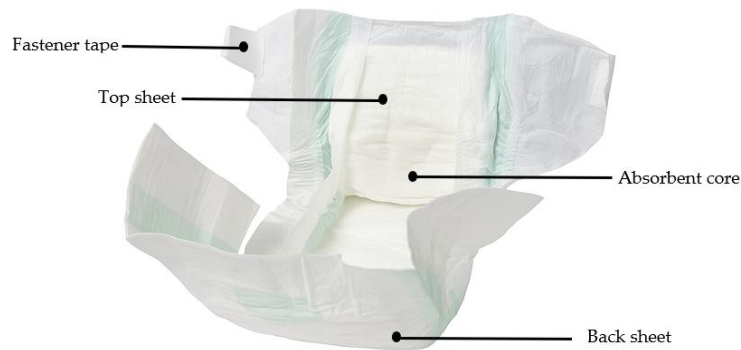


Figure 2.2. Components of commercial disposable diapers (Source: Author’s own (2025)).

The absorbent core consists of SAP gel, usually sodium polyacrylate mixed with cellulose, enclosed in a porous polymer layer (Baldwin et al., 2001). This core absorbs and retains urine and faeces, while the LDPE backsheet provides waterproofing but persists in the environment for centuries (Płotka-Wasyłka et al., 2022). The backsheet, made from low-density polyethylene (LDPE), provides a waterproof outer layer to prevent leakage.

2.2.2 *Environmental Impact and Disposal Challenges*

In low- and middle-income countries, inadequate waste management infrastructure leads to diapers being discarded in municipal solid waste, landfills, or the environment. Disposal practices are often unregulated, and public awareness of sustainable alternatives is limited (Płotka-Wasyłka et al., 2022). Improper disposal contributes to environmental accumulation of non-biodegradable materials and faecal pathogens, posing risks to human health, domestic animals, and ecosystems (Kordecki et al., 2022).

Disposable diapers generate substantial waste: an average infant uses ~5000 diapers before toilet training, producing approximately 1 ton of waste per year. In households with children in diapers, these products can account for 50% of household waste and represent 1.5–4% of municipal solid waste (Meseldzija et al., 2013). Conventional diapers composed mainly of polyethylene and polypropylene can persist for hundreds of years in landfills due to their resistance to microbial degradation (estimated > 400 years in some studies (Patel et

al.,2011). Improper disposal introduces multiple environmental hazards. Water contamination may occur, as landfilled diapers can leach chemicals and pathogens (e.g., hepatitis B, poliovirus) into groundwater, affecting drinking water safety (Meseldzija et al., 2013). Air pollution results from the open burning releases dioxins, furans, phthalates, carbon monoxide, and particulate matter, posing respiratory risks (Ntekpe et al.,2020; Shah et al., 2024). Soil contamination and bioaccumulation are also of concern, as hazardous chemicals from diapers can accumulate in soil and aquatic ecosystems, impacting fish and entering the food chain (Hondo et al., 2020). Furthermore, discarded diapers provide breeding grounds for flies and mosquitoes, increasing the risk of diarrhoea and vector-borne illnesses (Crunivel et al., 2020). Additionally, diaper waste contributes to urban and drainage issues, including sewer blockages, drainage obstruction, flooding, and urban aesthetic degradation (Imam et al., 2008).

2.3 Biodegradable Diaper Alternatives

2.3.1 Definition and Key Characteristics

Biodegradable polymers are defined as materials that undergo microbially induced chain scission, resulting in mineralisation (Nayak,1999). Biodegradation, also known as biotic degradation, involves the breakdown of polymer substances in the presence of living organisms such as algae, fungi, and bacteria. Microorganisms utilise biodegradable polymers as a source of energy and nutrients, producing progressively smaller molecules that enter cellular metabolic pathways such as the Krebs cycle. This process ultimately converts polymers into water, carbon dioxide, biomass, and other non-toxic by-products (Kržan, 2012).

Biodegradable diaper materials are evaluated not only for their degradation rates but also for mechanical performance, cost, and safety (Mirabella et al., 2013). PLA and PBAT have been widely studied due to their commercial availability and compliance with compostability standards (Myalenko and Fedotova, 2023), whereas natural fibres such as bamboo and organic cotton offer rapid biodegradability and hypoallergenic properties (Amjad, 2024). Each material presents trade-offs: PLA is brittle but renewable, PBAT is flexible but expensive, and natural fibres require careful processing to maintain absorbency.

2.3.2 *Types of Biodegradable Diaper Materials*

2.3.2.1 Bamboo and Organic Cotton

Bamboo, a member of the Poaceae family, is a rapidly renewable source of cellulose fibres, with species such as *Phyllostachys edulis* widely used in textile applications (Shanmugasundaram and Gowda, 2010). Bamboo fibres contain natural antibacterial compounds, such as bamboo kun, and exhibit high water absorbency and breathability, making them suitable for hypoallergenic diaper designs.

Organic cotton, cultivated without synthetic pesticides or fertilizers, provides environmental and social benefits, including reduced water contamination and improved working conditions (Tamta and Kamoj, 2024). Bamboo's natural antimicrobial properties reduce the risk of diaper rash (Malarvizhi, 2015), while organic cotton minimizes chemical exposure for infants (Rovira and Domingo, 2019). These fibres degrade within 2–3 months under composting conditions, significantly faster than LDPE. However, water-intensive cultivation of cotton may offset some environmental benefits (Zhang et al., 2023) Studies indicate that blends of bamboo and organic cotton perform well in terms of absorbency, liquid permeability, and rewettability, making them feasible alternatives to conventional materials in disposable diapers (Shanmugasundaram and Gowda, 2010).

2.3.2.2 Polybutylene Adipate-Co-Butylene Terephthalate

PBAT is a synthetic, fully biodegradable copolymer composed of adipic acid, terephthalic acid, and 1,4-butanediol (Roy et al., 2024; Xing et al., 2019). It demonstrates high elongation at break, ductility, and compostability. Under industrial composting conditions, PBAT-based materials can degrade completely within three to six months (Jian et al., 2020). PBAT meets the required standard for plastics designed for aerobic composting in municipal or industrial facilities (ASTM D6400) and for packaging recoverable through composting and biodegradation (EN 13432) (ASTM D6400,2023; EN 13432,2000). However, its high production cost and certain mechanical limitations still restrict its large-scale application (Roy et al., 2024; Touchaleaume et al.,2016). Comparative studies show that PBAT is more

flexible than PLA but less suitable for home composting due to slower degradation at ambient temperatures (Myalenko and Fedotova, 2023).

2.3.2.3 Polylactic Acid

PLA is a thermoplastic polymer derived from renewable feedstocks such as corn and sugarcane. It exhibits similar functional properties to LDPE, traditionally used in diaper backsheets, but is biodegradable and can be processed using conventional polymer processing equipment (Henton et al., 2005). PLA-based diapers can achieve comparable absorbency to conventional products while reducing environmental persistence. Strategies such as blending PLA with PBAT, copolymerisation, and addition of biodegradable fillers can improve its mechanical performance (Zhao et al., 2020; Olonisakin et al., 2025). Studies indicate that PLA-based backsheets can achieve comparable absorbency to LDPE, with lower carbon footprint (Kaptan and Kartal, 2024).

2.3.2.4 Other Biopolymers Explored

Polybutylene succinate (PBS) and polyhydroxyalkanoates (PHAs) have been explored as potential diaper materials. PBS offers good clarity, flexibility, and processability, but its brittleness and cost may limit practical applications (Barletta et al., 2022; Rafiqah et al., 2021). PHAs are microbial polyesters with thermoplastic and elastomeric properties that degrade readily into water and carbon dioxide, although industrial-scale production remains costly and challenging (Philip et al., 2007; Wang et al., 2014).

Table 2.1 provides a comparative overview of barrier and topsheet materials based on barrier strength, Water Vapor Transmission Rate and flexibility. Low-density polyethylene (LDPE) provides excellent flexibility and waterproofing, but it is highly hydrophobic and non-biodegradable. It exhibits very low water vapor transmission rates (WVTRs) and high barrier strength, which makes it effective at preventing leakage, but it persists in the environment for centuries (Płotka-Wasyłka et al., 2022; Iskandar et al., 2025). By comparison, PLA offers moderate barrier properties due to its hydrophobic nature, which restricts its application for high-barrier packaging unless it is blended (Mohsen and Ali, 2018). In contrast, PBAT has very high flexibility and moisture resistance but has a lower barrier strength (Debeli et al., 2023;

Elhamnia et al., 2023). When added to polymers, natural fibres like bamboo and organic cotton can improve gas barrier qualities by forming a more intricate diffusion channel; nevertheless, because they are hydrophilic, these materials have a high WVTR (Jayarathna et al., 2022; Nautiyal and Vasugi, 2018). While organic cotton is softer and a bit more pliable than bamboo fibres, both tend to lessen the flexibility of polymers when added to composites (Nautiyal and Vasugi, 2018; Tiwari and Turner, 2014).

Table 2.1. Barrier and topsheet materials (Source: Author’s own (2025)).

Material	Barrier Strength	Water Vapor Transmission Rate (WVTR)	Flexibility	Reference
Low-density polyethylene	Good	Very low	High	(Plotka-Wasyłka et al., 2022; Iskandar et al., 2025)
Polylactic acid	Moderate	High	Low	(Mohsen and Ali, 2018)
Polybutylene adipate-co-terephthalate	Good	Lower than PLA	Very high	(Debeli et al., 2023; Elhamnia et al., 2023)
Bamboo fibre	Good	High	Very low	(Jayarathna et al., 2022; Nautiyal and Vasugi, 2018)
Organic cotton	Good	Very high	Moderate	(Jayarathna et al., 2022; Nautiyal and Vasugi, 2018)

Superabsorbent polymers are good for hygiene products since they have the largest absorbency and liquid retention capacity (Meshram et al., 2020). However, because of their synthetic composition, SAPs are not very biodegradable (Płotka-Wasyłka et al., 2022). Chitosan hydrogels are environmentally beneficial substitutes because of their great biodegradability and biocompatibility, moderate to high absorption, and good retention (Michalik and Wandzik, 2020; Ahmadi et al., 2015). Despite its poor retention and reduced absorbency, cellulose is a desirable natural absorbent or reinforcing material in biodegradable composite systems since it is extremely sustainable and biodegradable (Ragab et al., 2025).

For convenience, Table 2.2 summarises the advances and challenges of core superabsorbent materials.

Table 2.2. Core absorbent materials (Source: Author’s own (2025)).

Material	Absorbency Capacity	Retention	Biodegradability	Reference
SAPs	Very high	Excellent	Non-biodegradable	(Płotka-Wasyłka et al., 2022; Meshram et al., 2020)
Cellulose	Moderate	Moderate	Biodegradable	(Michalik and Wandzik, 2020; Ahmadi et al., 2015)
Chitosan hydrogels	High	Good	Biodegradable	(Ragab et al., 2025)

Additionally, nanocellulose-based hydrogels are an especially promising class for replacing SAPs. When properly crosslinked, they can achieve compostable behaviour suitable for hygiene products (e.g., diapers) and show favourable swelling and retention properties. Their

use is discussed broadly in recent reviews of cellulose-based SAPs for personal care applications. A particularly compelling example comes from fully bio-based, thermally crosslinked SAPs derived from citric acid, monosodium citrate, and glycerol (no acrylate monomers). These materials obtained $\sim 24 \text{ g g}^{-1}$ absorbency and exhibited $\sim 40\%$ biodegradation over 28 days in activated sludge assays (Chen, 2025). Despite these advances, none of the current biodegradable alternatives yet match the combination of absorption capacity, retention under load, polymer stability, and cost performance of conventional sodium polyacrylate. As such, the development of scalable, high-performance biodegradable SAPs remains a key research frontier alongside the replacement of polyolefin outer layers.

2.3.3 *Manufacturing Processes and Sustainability Considerations*

The production of biodegradable diaper materials varies depending on the polymer type, with distinct environmental and practical implications. Bamboo fibres are extracted using mechanical or eco-friendly chemical methods that preserve antimicrobial properties while minimizing chemical effluents (Wang et al., 2008). Organic cotton cultivation avoids synthetic pesticides and fertilizers, reducing environmental impact and safeguarding human health (Muhammad and Muhammad, 2010).

PLA is industrially synthesised via fermentation of renewable feedstocks into lactic acid, followed by polymerisation. Industrial composting of PLA significantly reduces its environmental footprint compared to conventional plastics, though energy-intensive polymerisation steps may offset some sustainability benefits (Feghali et al., Rezvani et al., 2020). PBAT and PBS are produced through condensation polymerisation of their constituent acids and diols. Despite complete biodegradability, their higher cost and energy requirements limit widespread use (Roy et al., 2024; Rafiqah et al., 2021).

A critical engineering dilemma arises from the need for diapers to remain stable during use but degrade rapidly post-disposal. Addressing this paradox requires materials that respond to compost-specific triggers such as moisture, temperature, or enzymatic cues (Hossain, 2024). The literature suggests that material choice and processing techniques strongly

influence the environmental sustainability and practical feasibility of biodegradable diapers. Optimising manufacturing efficiency while maintaining biodegradability, safety, and comfort remains an important area for further research.

2.3.4 Biodegradability Mechanisms and Sustainable Considerations

The biodegradation of polymers used in disposable diapers depends on both the chemical structure of the polymer and the environmental conditions to which it is exposed (Kržan, 2012). Fundamentally, biodegradation can occur through oxidation-based or hydrolysis-based reactions, which may act sequentially or simultaneously. Condensation polymers such as polyesters and polyamides predominantly degrade via hydrolysis, while polymers with a carbon-only main chain, such as lignin or polyvinyl alcohol, undergo oxidation followed by hydrolysis of chains following oxidative cleavage (Kržan, 2012).

Poly(lactic acid) and poly(butylene adipate-co-terephthalate) have been the most widely studied biopolymers in diaper applications due to their commercial availability, cost-effectiveness, and relative biodegradability. PLA undergoes enzymatic hydrolysis, a zipper-like depolymerisation mechanism, which breaks macromolecular chains into smaller fragments that are further mineralised into carbon dioxide and water (Weng et al., 2013; Ghorpade, 2001). Factors such as molecular weight, degree of crystallinity, purity, and presence of stabilisers affect the degradation rate (Park et al., 2009; Rudnik and Briassoulis, 2011). PLA typically degrades within 6–12 months under industrial composting conditions (≈ 58 °C, high humidity, controlled microbial activity) but may persist for several years in ambient or landfill environments, whereas PBAT blends can fully decompose in 90 days to six months (Jian et al., 2020). Bamboo and organic cotton fibres also exhibit high biodegradability, with composting times of 2–3 months and 3 months, respectively (Shanmugasundaram and Gowda, 2010).

Table 2.3 summarises typical decomposition times for various biodegradable and conventional diaper materials. The data illustrates that while LDPE persists in landfills for centuries, biopolymers such as PLA, PBAT, bamboo, and organic cotton exhibit significantly faster biodegradation under appropriate conditions.

Table 2.3. Biodegradation rates of different diaper materials (Source: Author’s own (2025)).

Material	Decomposition Time in Landfills (Years/Months)	Decomposition Time in Composting Facilities (Months)	References
Low-density polyethylene	500+ years	Not compostable	(Meseldzija et al., 2013).)
Polylactic acid	2–5 years	6–12 months under industrial composting conditions	(Ghorpade, 2001; Leejarkpai et al., 2011)
Polybutylene adipate-co-terephthalate	3–6 months	3 months	(Jian et al., 2020)
Bamboo fibre	6 months	3 months	(Shanmugasundaram and Gowda, 2010).
Organic cotton	5 months	2–3 months	(Tamta and Kamoj, 2024).

Environmental conditions strongly affect degradation rates. In tropical regions with high humidity and temperatures above 30 °C, microbial activity and hydrolysis accelerate biodegradation of bamboo and organic cotton, often reducing composting time to under 8 weeks (Bher et al., 2022). Conversely, PLA degrades poorly at ambient tropical temperatures due to its high glass transition temperature, requiring industrial composting for efficient breakdown (Lin et al., 2025). Such climate-linked degradation dynamics must be considered when implementing biodegradable diapers in African and Asian contexts.

The effective end-of-life management of biodegradable diapers can further enhance environmental benefits. Industrial composting is particularly promising for PLA, PBAT, and natural fibres. As illustrated in Figure 2.3, collected diapers are sorted to separate plastics from organic material. The organic fraction, including SAPs and faecal residues, is combined with cow dung, earthworms, or activated bacteria and composted under controlled pH and moisture to produce stabilised, sanitised compost (Tamta and Kamoj, 2024).

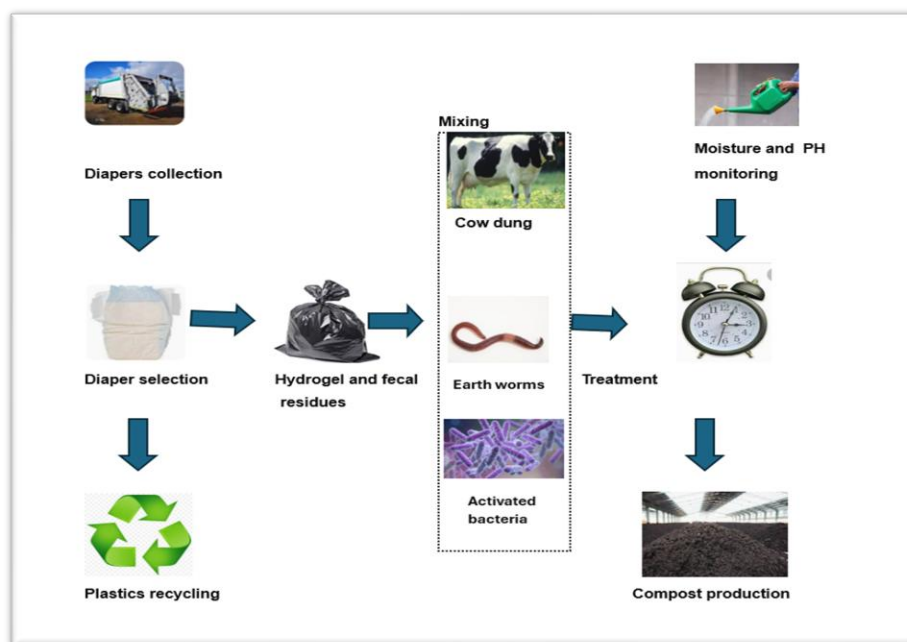


Figure 2.3. Flowchart illustrating the key steps in industrial composting, from collection to the final compost product. (Source: Adapted from (Ferronato et al,2020)) [open access].

This synthesis highlights that while conventional LDPE-based diapers persist in the environment for centuries, alternative biodegradable polymers offer faster decomposition rates and can be integrated into sustainable waste management strategies. Additionally, selecting materials with known biodegradation mechanisms ensures both environmental safety and compliance with industrial composting standards, addressing key concerns regarding long-term ecological impact.

2.4 Performance and Safety

The successful adoption of biodegradable diapers depends on their ability to balance environmental benefits, product performance, consumer acceptance, and infant safety.

These dimensions are critical for ensuring market viability, human health, and practical utility (Mendoza et al., 2019; Saifudeen, 2019).

2.4.1 Absorbency and Leakage Prevention

Diaper performance is primarily determined by liquid absorption, retention, and leakage prevention. Conventional diapers achieve this through a combination of SAPs and cellulose (Baldwin et al., 2001, Dey et al., 2016). Biodegradable alternatives, such as PLA, PBAT, bamboo, and organic cotton, can reach comparable absorbency when blended with absorbent cores or reinforced with natural fibres. For example, bamboo–cotton blends demonstrate high liquid retention and low rewetting, while PLA-based backsheets, when plasticised or blended with flexible polymers such as PBAT, can replicate the barrier properties of LDPE without losing flexibility (Shanmugasundaram and Gowda, 2010; Henton et al., 2005). Nonetheless, variability in natural fibres or material heterogeneity can cause inconsistencies in performance, highlighting the need for standardized manufacturing protocols (Konstantopoulos, 2019).

2.4.2 Comfort and Skin Health

Softness, breathability, and hypoallergenic properties are equally important in determining infant comfort. Bamboo fibres, containing natural antimicrobial and moisture-wicking compounds (bamboo kun), reduce the risk of diaper rash and irritation (Shanmugasundaram and Gowda, 2010). Organic cotton provides similar benefits and avoids pesticide residues associated with conventional cotton (Tamta and Kamoj, 2024). In contrast, PLA and PBAT may require copolymerisation or plasticiser incorporation to achieve the softness and flexibility needed for sensitive infant skin (Zhao et al., 2020). Studies report that infants wearing bamboo or organic cotton blends experience fewer skin issues than those using conventional SAP–LDPE diapers (Shanmugasundaram and Gowda, 2010).

2.4.3 Consumer Perception and Acceptance

Parents often express interest in eco-friendly diaper alternatives, but purchasing decisions remain influenced by performance, convenience, and price (Maraveas, 2020; White, 2023). If biodegradable diapers are significantly more costly than conventional products, uptake

remains limited despite ecological benefits. Effective communication of product advantages, including biodegradability, safety, and compliance with international standards, is essential to improve market adoption. Additionally, cultural factors play a role, as disposal practices differ across regions; in some low- and middle-income countries, open dumping remains common despite awareness of sustainable options (Kimani et al., 2015).

2.4.4 Health and Safety Considerations

An important requirement for biodegradable diapers is the absence of harmful substances such as phthalates, bisphenol-A, and heavy metals, which are often detected in conventional plastics (Shah et al., 2024, Hondo et al., 2020). Materials such as PLA, PBAT, bamboo, and organic cotton generally demonstrate low toxicity and are safe for infants when appropriately processed (Mondal, 2021). However, additives, coatings, or blended polymers must be carefully evaluated for allergenicity or leaching risks during prolonged skin contact. Regulatory compliance and adherence to safety testing standards are vital to ensure consumer trust and infant well-being (Makoś-Chełstowska, 2021)

Performance and safety also extend to the disposal phase. Biodegradable diapers that maintain absorbency while being compostable contribute to industrial or home composting, reducing landfill volumes and pollution. Composting of organic cores and recycling compatible bioplastics can enhance the sustainability profile of these alternatives (Fu et al., 2020; Ferronato et al., 2020). Taken together, biodegradable diapers can match or approach the functionality of conventional products, but successful adoption depends on simultaneously optimizing absorbency, comfort, safety, affordability, and integration with waste management systems as shown in Table 2.4.

Table 2.4. Performance and safety of biodegradable diaper alternatives (Source: Author’s own (2025)).

Material	Absorbency and Leakage Prevention	Comfort and Skin Health	Consumer Perception and Acceptance	Health & Safety Considerati ons	Integration with Waste Management	References
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Low-density polyethylene	Good	Smooth	Positive	Contain toxins	Limited waste management approach	Shah et al, 2024; (Baldwin et al., 2001; Hondo et al., 2020; Dey et al., 2014)
Polylactic acid	Good when blended	Rough, copolymerisation required	Positive, limited by lack of information	Low toxicity and safe	Numerous treatment options.	(Fu et al., 2020; Shanmugasundaram and Gowda, 2010; Henton et al., 2005; Zhao et al., 2020; Ferronato et al., 2020; Maraveas, 2020; Mondal, 2021)
Polybutylene adipate-co-terephthalate	Better	Rough, copolymerisation required	Positive, limited by lack of information	Low toxicity and safe	Numerous treatment options.	(Zhao et al., 2020; (Ferronato et al., 2020; White, 2023; Mondal, 2021)
Bamboo fibre	Good	Smooth	Positive, limited by lack of information	Low toxicity and safe	Numerous treatment options.	(Fu et al., 2020; Shanmugasundaram and Gowda, 2010; Henton et al., 2005; Ferronato et al., 2020; Maraveas, 2020; Mondal, 2021)

Cotton	Good	Smooth	Positive, limited by lack of information	Low toxicity and safe	Numerous treatment options.	(Shanmugasundar am and Gowda, 2010; Henton et al., 2005; White, 2023; Mondal, 2021; Makoś- Chetstowska, 2021; Tamta, 2024)
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2.5 Environmental and Economic Barriers

Despite clear environmental advantages, the transition from conventional to biodegradable diapers faces technical, economic, and social barriers. Adoption depends not only on ecological benefits but also on achieving cost-effectiveness, scalability, and consistent product performance.

2.5.1 Cost and Affordability: Comparison of Biodegradable Polymers vs. Conventional Polymers

There is a noticeable trade-off between environmental performance and economic viability when comparing the costs of biodegradable and conventional polymers. High production costs of bio-based polymers remain a critical limitation. For instance, PHAs are significantly more expensive than petroleum-based plastics due to complex microbial synthesis and reliance on carbon-rich feedstocks (Maraveas, 2020). PHA and chitosan composites are examples of advanced bio-based materials that may cost more than \$6 per kilogram (Gundlapalli et al., 2025). While microbial engineering and mixed-culture fermentation have shown potential to reduce costs, these processes often yield lower productivity and volumes (Maraveas, 2020, Tsang et al., 2019). Because of their established production infrastructure, abundant fossil feedstocks, and great manufacturing efficiency, conventional plastics like low-density polyethylene (LDPE) are still substantially less costly, usually costing ~\$1/kg (Hernández et al., 2023).

The price of biodegradable polymers, such as polylactic acid (PLA) and poly(butylene adipate-co-terephthalate) (PBAT), ranges from \$2.5 to 5.0 per kilogram, which is mostly due to the high cost of raw ingredients, fermentation-based manufacture, and smaller production quantities (Dallaev et al., 2025). Although blending with natural fibres or optimizing fermentation can lower expenses, these strategies may compromise mechanical properties (Tripathi et al., 2021). They provide long-term environmental and waste management benefits by lowering pollutants, carbon emissions, and landfill usage, despite their high initial cost (Weng et al., 2013). Market research suggests that parents often prioritize performance and affordability over environmental benefits, limiting willingness to pay a premium for biodegradable options (Maraveas, 2020; White, 2023). Therefore, cost reductions must be coupled with equivalent performance to achieve widespread adoption.

2.5.2 Production Scalability and Supply Chain Constraints

Even when production technologies exist, scalability remains a challenge. For example, a company with an annual production capacity of 50,000 tonnes of PHAs reported selling less than 500 tonnes annually due to low adoption, leading to closure (Wu et al., 2023). Reliable feedstock availability, efficient supply chains, and stable consumer demand are essential to sustain commercial production. Without this, investment in large-scale facilities may not be viable.

2.5.3 Performance Consistency and Product Design

Consistency in product performance is another barrier. Biodegradable polymers such as PLA and PBAT often require reinforcement with fibres, plasticisers, or copolymers to match the flexibility, absorbency, and durability of LDPE-based diapers (Henton et al., 2005; Zhao et al., 2020). Variability in fibre quality or polymer blends can lead to unpredictable results, which undermines consumer trust. At the same time, maintaining infant safety requires minimizing the use of additives or chemicals that may leach during wear, posing risks of irritation or toxicity (Shah et al., 2024; Hondo et al., 2020).

Table 2. 5 summarizes the existing barriers to adoption of the promising diaper alternatives. In general, the adoption of biodegradable diapers is constrained by high costs, limited

scalability, and inconsistent performance. Addressing these barriers through innovations in material science, supply chain improvements, and cost optimization is essential to enable meaningful market penetration.

Table 2.5. Barriers to adoption of biodegradable diapers (Source: Author’s own (2025)).

Material	Cost Affordability	Production	Performance	References
		and Scalability Supply Chain Constraints	and Consistency and Product Design	
Polyhydroxyal kanoates	Highly expensive	Limited	Flexible	(Wu et al., 2023)
Polylactic acid	Less expensive	Limited	Not flexible, require reinforcement	(Henton et al., 2005; Zhao et al., 2020; Naser et al. ,2021)
Polybutylene adipate-co- terephthalate	Moderately expensive	Limited	Flexible	(Henton et al., 2005; Zhao et al., 2020)
Bamboo fibre	Moderately expensive	Limited	Flexible	(Malarvizhi, 2015)
Cotton	Moderately expensive	Limited	Flexible	(Malarvizhi, 2015; Tamta, 2024)

2.6 Policy, Waste Infrastructure, and Social Acceptance

Although biodegradable diapers have advanced significantly, further research is needed to enhance material performance, ensure safety, and validate environmental sustainability. The following areas highlight promising directions for future innovation.

2.6.1 *Material Innovation and Optimization*

Current biopolymers such as PLA and PBAT show promise as alternatives to LDPE, but their brittleness and limited flexibility restrict direct application in diapers (Henton et al., 2005; Zhao et al., 2020). Strategies such as blending, copolymerization, and nanofiller reinforcement could improve mechanical properties and durability (Zhao et al., 2020). Reinforcement with biodegradable fibres or nanocomposites may also enhance absorbency and structural integrity (Weng et al., 2013). Surface modification techniques, including hydrophilic treatments or antimicrobial coatings, could further improve comfort and moisture management, thereby aligning product performance with consumer expectations.

2.6.2 *Safety and Toxicity Assessment*

Ensuring infant safety remains paramount. While PLA, PBAT, bamboo, and organic cotton generally exhibit low toxicity, additives and coatings must be evaluated for allergenicity or chemical leaching (Shah et al., 2024; Hondo et al., 2020). Future research should focus on identifying potential chemical by-products under real-world conditions, assessing allergenic or cytotoxic risks, and establishing standardized eco-toxicity and safety testing protocols. Strengthening regulatory frameworks will also be crucial to gain consumer trust and meet international standards (Saifudeen, 2019).

2.6.3 *Biodegradation Pathways and Environmental Fate*

Understanding how biodegradable polymers decompose under practical conditions is critical to validating their sustainability claims. Comparative studies on industrial composting versus home composting can clarify decomposition rates and end-of-life pathways (Sikorska et al., 2021; Xulu et al., 2023). Monitoring potential release of microplastics or chemical residues during degradation is equally important to prevent unintended environmental impacts (Makoś-Chełstowska, 2021). Life cycle assessment (LCA) models should be expanded to quantify the true environmental footprint of biopolymer-based diapers and guide both manufacturers and policymakers (Mirabella et al., 2013).

Table 2.6 highlights the key strategies and research directions for advancing alternative biodegradable materials for disposable diapers. Exploring and implementing the

recommended will ensure the development of more efficient, environmentally responsible and safer biodegradable diapers.

Table 2.6. Areas of focus for future innovation (Source: Author’s own (2025)).

Element	Strategies	References
Material Innovation and Optimization	Improve biopolymer mechanical properties, explore surface and modification techniques.	(Henton et al., 2005; Zhao et al., 2020; Weng et al., 2013).
Safety and Toxicity Assessment	Identification of by-products, allergic risks assessment, safety testing and eco-toxicity protocols.	(Shah et al., 2024; Hondo et al., 2020; Dey et al., 2016)
Biodegradation Pathways and Environmental Fate	Expansion of LCA models, monitoring potential release of microplastics during degradation.	(Mirabella et al., 2013; Gundlapalli et al., 2025; Sikorska et al., 2021; Xulu et al., 2023)

Future progress in biodegradable diapers requires a multi-pronged approach: material innovation to close the performance gap with conventional products, rigorous safety assessment to protect infant health, and deeper investigation into degradation processes to ensure environmental benefits are fully realized. These directions will determine whether biodegradable diapers can transition from niche alternatives to mainstream solutions.

2.7 Conclusions

This review highlights the potential of biodegradable polymers to reduce the environmental burden of disposable diapers. PLA, PBAT, bamboo, and organic cotton represent viable alternatives to conventional LDPE-based products, offering benefits in terms of

biodegradability, renewable sourcing, and reduced landfill persistence. However, each material presents limitations: PLA is brittle, PBAT and PHAs are costly, and natural fibres require careful processing to meet absorbency and mechanical performance standards. Equally critical is the replacement of sodium polyacrylate-based SAPs. Recent research into polysaccharide-based hydrogels, chitosan, and nanocellulose demonstrates progress toward biodegradable SAPs, yet their performance and scalability remain insufficient compared to conventional SAPs.

Adoption of biodegradable diapers faces barriers related to cost, supply chain constraints, and consumer acceptance, emphasizing the need for scalable production methods and strategic education on environmental benefits (Mendoza et al., 2019; Saifudeen, 2019). Market acceptance depends on achieving functional parity with conventional diapers in absorbency, comfort, and safety, while communicating environmental benefits effectively (Iskandar et al., 2025). Furthermore, effective waste management systems, including industrial composting and proper collection, are critical to ensuring the environmental advantages of these materials are realized. End-of-life management ensures that rapid biodegradation occurs without generating secondary pollutants, such as microplastics (Sikorska et al., 2021). Future progress will depend not only on replacing polyolefin-based outer layers but also on advancing high-performance, biodegradable SAP systems to enable the development of truly sustainable diaper products.

Future research should focus on the development of SAPs incorporating compost-triggered degradation mechanisms. Additionally, there is a need to design multi-layer structures where only outer layers biodegrade under controlled conditions, ensuring both performance stability during use and efficient degradation post-disposal. Moreover, integrating cost-reduction strategies through the inclusion of bio-fillers and the valorisation of waste materials presents an important avenue for improving the economic feasibility and sustainability of biopolymer-based disposable diapers. Researchers must assess health and safety implications for infants, including potential chemical leachates and allergenicity. Finally, investigating biodegradation pathways under diverse environmental conditions and evaluating life-cycle impacts—together with exploring cost-effective production and market

strategies to bridge the gap between technological potential and consumer adoption—will be important to translating these materials into practical, sustainable alternatives.

By addressing these challenges, biodegradable diaper alternatives can provide practical, sustainable solutions that reduce landfill accumulation, minimize public health risks, and support circular economy practices in waste management. Integrating material innovation, consumer awareness, and effective disposal strategies will be critical to advancing the adoption of environmentally responsible diaper products globally. Therefore, despite clear environmental advantages, widespread adoption will depend on overcoming economic barriers, improving waste management infrastructure, and adapting products to the climatic conditions of high-humidity regions.

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Chapter 3

Methodology

3.1 Overview

This chapter outlines the materials, experimental procedures, and equipment used to investigate the composition of commercial disposable diaper backsheets. It details the selection and preparation of diaper samples and reference films, which are LDPE and PLA. Moreover, it provides a comprehensive description of the biodegradation testing using organic compost.

3.2 Materials

Three commercial disposable diapers from different brands were purchased from a local retail store. To maintain confidentiality, the extracted backsheet samples were labelled as Diaper A, Diaper B, and Diaper C. LDPE and PLA films were used as reference materials. LDPE pellets were supplied by Sasol Polymers, while PLA pellets were purchased from 2M BIOTEC LLP 180 Annal Gandhidigal Salai, Ramanathapuram 623501, TN in India. Organic compost, serving as the biodegradation medium, was purchased from a local garden supply store.

3.3 Sample preparation

The LDPE and PLA pellets were first dried overnight at 50°C in a vacuum oven to remove moisture. The samples were then melt-pressed into 0,5 mm thick sheets using a hydraulic press for five minutes at 180 °C under a pressure of 50 kPa. All films and diaper backsheets were cut into appropriate sizes for testing.

3.4 Sample characterisation

3.4.1 Differential scanning calorimetry

To examine thermal transitions, such as melting and crystallisation temperatures, a Perkin Elmer Pyris 6000 differential scanning calorimeter (DSC), made in Akron, OH, United States, was used (see Figure 3.1). All samples (~6,0 mg) were first heated from 0 to 180 °C, cooled from 180 to 0 °C and reheated from 0 to 180 °C at a rate of 10°C per minute. The phase

transition temperatures and enthalpies were determined from the cooling and second heating scans. The first heating scans were not used for calculations, but they were used for thermal history removal.



Figure 3.1. Perkin Elmer Pyris 6000 differential scanning calorimeter. Source: Author's own (2025)

3.4.2 Fourier transform infrared spectroscopy

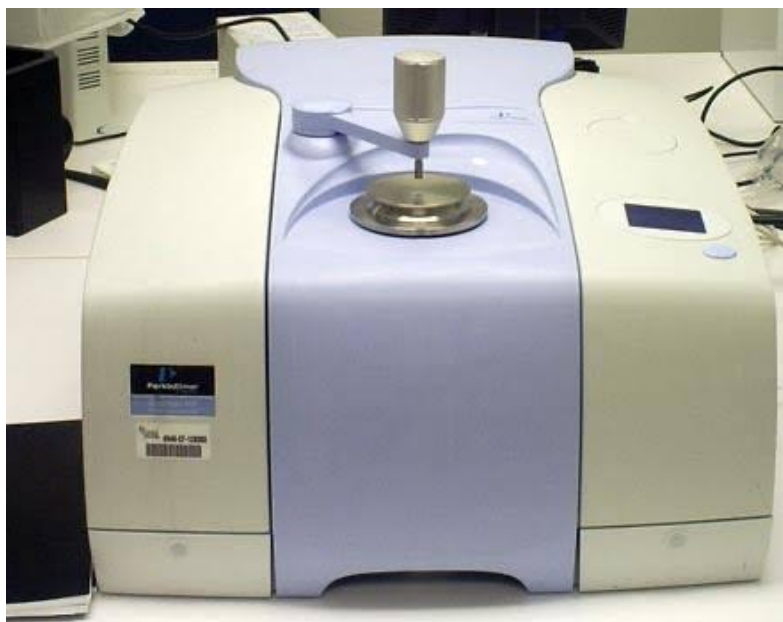


Figure 3.2. Perkin-Elmer SPECTRUM 100 series spectrometer. Author's own (2025)

To identify functional groups and confirm polymer composition, the Perkin-Elmer Spectrum 100 series spectrometer, produced by PerkinElmer, Inc., based in the United States, was used to analyse the samples (see Figure 3.2). It was outfitted with a diamond crystal and a PIKE Miracle™ ATR. In this instrument, the wave number was adjusted to between 450 and 4 000 cm^{-1} , and eight scans were run in total at a resolution of 4 cm^{-1} .

3.4.3 Scanning electron microscopy

To observe surface morphology and structural changes, a JEOL JSM-7800F extreme-resolution analytical field emission SEM (from Tokyo, Japan) was used (Figure 3.3). The samples were fractured, mounted on aluminium pin stubs using epoxy glue, and coated with iridium, using a Leica EM ACE600 high vacuum sputter coater from Vienna, Austria. SEM images were captured at 5 kV, at a working distance of 10 mm.



Figure 3.3. JEOL JSM-7800F Extreme-resolution analytical field emission scanning electron microscopy. Source: Fan et al. (2023)

3.4.4 Thermogravimetric analysis

To assess thermal stability and degradation behaviour, the Perkin-Elmer STA6000 thermogravimetric analyser, produced by Perkin-Elmer in Springfield, IL, United States, was used (Figure 3.4). A mass of approximately 0,025 g of each sample was heated between 30

and 650 °C, while circulated with a nitrogen atmosphere at a rate of 10°C per minute. The mass loss percentage was noted for each sample.



Figure 3.4. Perkin–Elmer STA6000 thermogravimetric analyser. Source: Author’s own (2025)

3.4.5 Biodegradation test

Biodegradation studies were conducted in accordance with the Standard Test Method for determining weight loss from plastic materials exposed to the simulated municipal solid-waste aerobic compost environment (ASTM D6003–96), using a stainless-steel container filler with organic compost. The compost was packed to a depth of 2 cm from the bottom of the container. Three test samples, namely Diaper C, LDPE and PLA, each weighing approximately 0,513 g, were placed on top of the compost with sufficient spacing between them to ensure uniform degradation as shown in Figure 3.5a.

Figure 3.5b shows the samples after they were completely covered with additional compost until the container was filled, with the depth of the samples from the top surface measured at 3 cm. The container was stored at room temperature (approximately 25°C), and the compost moisture was maintained by regularly sprinkling water, following the manufacturer’s instructions.

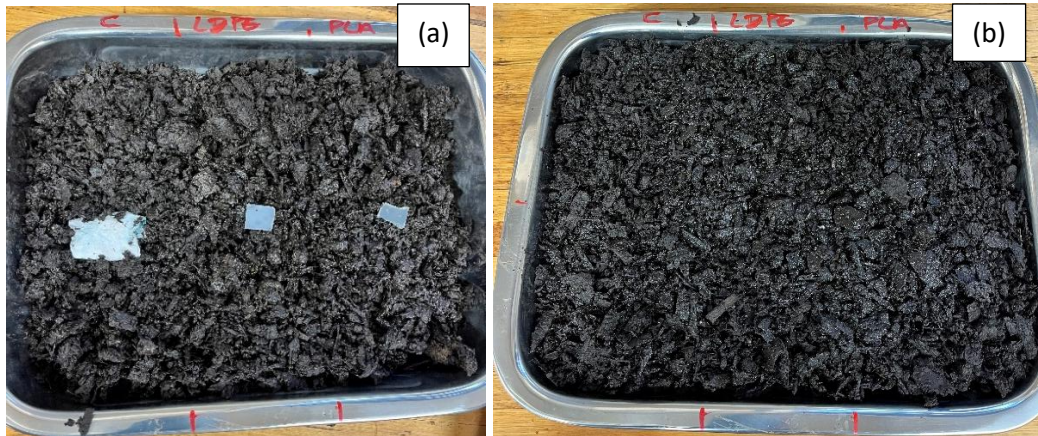


Figure 3.5. (a) Test samples before being completely covered with compost; (b) Test samples after being fully covered with compost. Source: Author's own (2025)

The biodegradation test was conducted over a period of 90 days. Samples were retrieved at 14-day intervals, cleaned with distilled water, dried in an oven set at 37 °C for 24 hours, and then weighed again, normalising the sample weight to the starting value each time, to ascertain the degree of integrability. Additionally, a qualitative assessment visual appearance of the films as they broke down in compost over time, was conducted using pictures (Sessini et al., 2018).

3.5 References

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Chapter 4

Results and Discussion

This chapter has been submitted to a peer-reviewed journal under the title:

Structural and Thermal Analysis of Commercial Diaper Backsheets: Assessing the Potential of Poly(Lactic Acid) for Biodegradable Applications

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Abstract

The increasing environmental impact of petroleum-based plastic waste has intensified the search for biodegradable alternatives, especially in single-use products such as disposable diapers. This study investigated the thermal, morphological and structural properties of three commercial diaper backsheets using differential scanning calorimetry (DSC), thermogravimetric analysis (TGA), scanning electron microscopy (SEM), fourier-transform infrared spectroscopy (FTIR) and soil burial biodegradation testing. Diapers A and B exhibited nearly identical thermal profiles, suggesting similar material compositions. Diaper C displayed distinct crystallization behavior, a more textured morphology and a two-phase degradation profile, indicating the presence of fibrous cellulose in addition to polyethylene (PE). Comparative analysis against reference materials showed that diaper C has a PE-based backsheet with physically-adsorbed cellulose fibres. Although this inclusion slightly alters the material's thermal and structural characteristics, it does not substantially enhance biodegradability. Biodegradation testing confirmed that part the cellulose fraction of diaper C degraded under composting conditions, while the PE component remained intact. In contrast, poly(lactic acid) (PLA) exhibited a lower decomposition temperature and gradual

mass loss under composting conditions, affirming its biodegradability. These findings support the potential of PLA-based backsheets as environmentally responsible alternatives that can reduce the long-term waste burden of PE-based disposable diapers.

Keywords: low-density polyethylene, biodegradable polymers, poly(lactic acid), disposable diapers, sustainable materials

4.1 Introduction

Disposable diapers are among the world's most widely used single-use consumer products, with billions being thrown away each year. Their environmental footprint is considerable, primarily due to the inclusion of non-biodegradable polymers in their construction, especially in the backsheet layer. As the global discourse on plastic pollution intensifies, researchers and industry stakeholders have emphasized the urgent need for sustainable alternatives. Numerous studies have been conducted on sustainable ways to address the impact of disposable diaper waste. Ntekpe et al. (2020) reported on the impact of disposal methods on public health and the environment where it was noted that although they are convenient, they contribute significantly to environmental pollution worldwide. The study revealed that disposable diapers are disposed haphazardly on the environment, which presents environmental and health challenges. In their conclusion, they argued that waste management authorities should create awareness on impacts as well as proper disposal of single-use diapers. Similarly, Itsubo et al. (2020) conducted a life cycle assessment of the closed loop of used disposable diapers where it was noted that about 23,5 billion disposable diapers are produced yearly. In their findings, they noted that the existing techniques used to treat disposable diapers have certain shortcomings. In their conclusion, they argued that landfilling and incineration of super absorbent polymers (SAPs) could decrease greenhouse gases. However, the said studies did not thoroughly investigate the compositional characteristics of commercial diaper backsheets or critically compared them with biodegradable polymers such as poly(lactic acid) (PLA). Polyethylene (PE), especially low-density polyethylene (LDPE), remains the most widely used polymer in diaper backsheets. This is due to its excellent moisture barrier properties, flexibility and low production cost. According to Greco et al. (2020), PE-based backsheets are thermally stable, with melting temperatures ranging from 112 °C to 138 °C, making them ideal for high-volume

manufacturing and daily use. The thermal stability is important for diaper production and performance. It allows the backsheet to withstand the heat associated with high-speed manufacturing processes. It also helps the material maintain its shape and impermeability during storage and transport in warm conditions. In addition, it ensures safety and comfort during use without deforming or losing barrier properties. Wong et al. (2002) further reported that PE composites in hygiene products exhibit high crystallinity and low permeability, which enhance product performance but simultaneously hinder biodegradation. In their analysis of PE-based composites, it was noted that the inert structure of polymers contribute to its extreme environmental persistence. As a result, used diapers can remain in landfills for up to 500 years without substantial breakdown.

In recent years, researchers have turned their attention to the integration of biodegradable polymers in single-use products (Mulungo V et al., 2025). PLA, a thermoplastic aliphatic polyester derived from renewable resources such as corn starch and sugarcane, has emerged as a promising candidate. Its biodegradability, compostability under industrial conditions and potential for carbon neutrality make it attractive for sustainable packaging and hygiene applications. Chen et al. (2003) observed that PLA has a relatively high glass transition temperature (60–65 °C) and a melting point between 150 and 160 °C. These thermal properties allow it to function in environments of moderate heat while retaining its compostability, provided that conditions such as humidity and microbial activity are favorable. Sharafi et al. (2022) also reported that the semi-crystalline nature of PLA gives it modest barrier properties, which can be enhanced through copolymerization or blending with fillers such as cellulose or starch nanocrystals. Despite its advantages, PLA has yet to be widely adopted in the diaper industry. One of the key challenges has been the trade-off between biodegradability and mechanical durability. According to Kfoury et al. (2013), PLA often requires structural reinforcement or plasticization to prevent brittleness and to match the performance of PEs. Nevertheless, when reinforced or blended appropriately, PLA has shown promise as a backsheet material in limited commercial trials. Furthermore, unlike PE, which leaves significant residue upon degradation, PLA tends to degrade completely into lactic acid, carbon dioxide and water, leaving no micro-plastics behind. Cellulose has also

been investigated as a biodegradable component in absorbent hygiene products. As a natural polymer composed of glucose units, cellulose is inherently hydrophilic and readily biodegradable under environmental conditions. While traditionally used in the absorbent core of diapers, its use in backsheet layers has been limited. However, some studies have explored the functional benefits of incorporating cellulose into polymer matrices. For instance, Asemani et al. (2020) found that cellulose can act as a nucleating agent in polymer blends, enhancing crystallization and potentially improving thermal behavior. These effects are valuable when targeting performance enhancement in biodegradable materials such as PLA or thermoplastic starch. Yildirim et al. (2015) used scanning electron microscopy (SEM) to detect the dispersion of cellulose within polymer matrices, noting that the fiber morphology significantly influenced degradation rates and mechanical properties. Recent studies have also applied advanced analytical techniques to evaluate polymer composition and degradation behavior. For example, Greco et al. (2008) and Ng et al. (2002) used differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) to characterize phase transitions, crystallinity and thermal stability in various plastic-based composites. DSC provides key insights into melting behavior, crystallization temperature and glass transitions, which help distinguish between different polymer types and detect the presence of blends or fillers. TGA offer complementary data by measuring thermal decomposition patterns and residual content, allowing inferences about the chemical structure and thermal stability of the material. Fourier-transform infrared (FTIR) spectroscopy has also been used to identify characteristic functional groups. Pasieczna-Patkowska et al. (2025) reported that C–H stretching vibrations between $2850\text{--}2950\text{ cm}^{-1}$ and C=O stretching around 1700 cm^{-1} are strong indicators of hydrocarbon chains and ester bonds, respectively. SEM is often used to visualize surface morphology and composition, supporting conclusions drawn from thermal and spectral analysis.

While the literature provides information on individual biodegradable polymers and traditional PE materials, comparative studies analysing commercial diaper backsheet compositions remain limited. Few investigations have characterized real-world products using a suite of analytical methods to explore their material identity and infer environmental

implications. Additionally, very little work has been done to explore whether existing diapers incorporate biodegradable additives such as cellulose or use multilayer constructions that might complicate recyclability. Given this context, the present study offers a novel contribution by applying DSC, TGA, FTIR and SEM to three commercially available diaper backsheets to determine their thermal, structural and morphological characteristics. Importantly, in addition to LDPE, the study introduces PLA as a reference biodegradable polymer to evaluate whether commercial backsheets could feasibly be replaced with more environmentally responsible alternatives. Through this multi-technique approach, the study bridges a critical gap in the literature and supports the development of sustainable hygiene products.

4.2 Experimental

4.2.1 Materials

Three commercial disposable diapers from different brands were purchased from a local retail store. To maintain confidentiality, the extracted backsheet samples were labeled as diaper A, diaper B, and diaper C. LDPE and PLA films were used as reference materials. LDPE pellets were supplied by Sasol Polymers, while PLA pellets were purchased from 2M BIOTEC LLP 180 Annal Gandhiadigal Salai, Ramanathapuram 623501, TN in India. A small amount of plant-derived cellulose, to be used as a reference, was donated by a lab in our department. Organic compost, serving as the biodegradation medium, was purchased from a local garden supply store.

4.2.2 Methods

Sample Preparation

The LDPE and PLA pellets were first dried at 50 °C in a vacuum oven overnight to remove moisture. The samples were then melt-pressed into 0.5 mm thick sheets using a hydraulic press at 180 °C for 5 minutes under a pressure of 50kPa. All films and diaper backsheets were cut into appropriate sizes for testing.

Biodegradation Test

The biodegradation test was conducted over a period of 90 days. The samples (0.5 g each) were retrieved at 14-day intervals, cleaned with distilled water, dried in an oven set at 37 °C for 24 hours, and then weighed again, normalizing the sample weight to the starting value each time, to ascertain the degree of integrability. The recorded weight loss of the samples was then converted to percentage using the following equation (Boonmee et al., 2016):

$$\text{Equation Weight Loss (\%)} = \left[\frac{(W_i - W_f)}{W_i} \right] \times 100$$

where the original dry weight (g) of the sample is denoted by W_i and the final dry weight after being recovered is represented by W_f . The average weight loss of three samples was used to calculate the weight loss percentage (Boonmee et al., 2016). Additionally, a qualitative assessment of the films' visual appearance as they broke down in compost over time was conducted using digital images.

4.2.3 Measurements

Differential scanning calorimetry (DSC)

To examine thermal transitions, such as melting and crystallization temperatures, a Perkin Elmer Pyris 6000 Differential Scanning Calorimeter, made in Akron, OH, USA was used. All samples (~ 6.0 mg) were first heated from 0 to 180 °C, cooled from 180 to 0 °C and reheated from 0 to 180 °C at the rate of 10 °C · min⁻¹. The phase transition temperatures and enthalpies were determined from the cooling and second heating scans. The first heating scans were not used for calculations, but they were used for thermal history removal.

Fourier-transform infrared spectroscopy (ATR-FTIR)

To identify functional groups and confirm polymer composition, the Perkin-Elmer Spectrum 100 series spectrometer, produced by PerkinElmer, Inc., based in the United States, was used to analyze the samples. It was outfitted with a diamond crystal and a PIKE Miracle™ ATR. In this instrument, the wavenumber was adjusted between 450 and 4000 · cm⁻¹, and eight scans were run in total at a resolution of 4 cm⁻¹.

Scanning electron microscopy (SEM)

To observe surface morphology and structural changes, a JEOL JSM-7800F Extreme-resolution Analytical Field Emission SEM (from Tokyo, Japan) was used. The samples were fractured, mounted on aluminum pin stubs using epoxy glue, and coated with Iridium using a Leica EM ACE600 High Vacuum Sputter Coater (from Vienna, Austria). SEM images were captured at 5 kV, at a working distance of 10 mm.

Thermogravimetric analysis (TGA)

To assess thermal stability and degradation behavior, the Perkin-Elmer STA6000 thermogravimetric analyzer, produced by Perkin-Elmer in Springfield, IL, USA, was used. A mass of approximately 25 mg of each sample was heated between 30 and 650 °C while circulated with a nitrogen atmosphere at a rate of 10 °C · min⁻¹. The mass loss percentage was noted for each sample.

4.3 Results and discussion

DSC experiments were conducted to investigate the thermal properties and crystalline structure of three commercial diaper backsheets, namely: diapers A, B and C (to preserve the identity of the manufacturer). This was to identify their polymer constituents and evaluate the potential of PLA as a biodegradable alternative to PE. In the cooling thermograms (Figure 4.1a), diapers A and B showed two distinct crystallization peaks, occurring sequentially around 95–100 °C and 110–115 °C. This dual crystallization behavior is characteristic of mixed-phase PE systems, such as blends of LDPE with linear low-density polyethylene (LLDPE) or high-density polyethylene (HDPE), where differences in chain branching and crystallization kinetics lead to multiple crystallization events. The proximity of the two exothermic events suggests fast and overlapping phase crystallization, consistent with industry-grade multilayer PE films used in hygiene products. Diaper C, in contrast, exhibited a small crystallization exotherm around 50–85 °C, followed by a prominent peak at 110 °C. The low-temperature peak is not seen in diapers A and B, but is present in pure LDPE, highlighting similar crystallization behavior between diaper C and LDPE. The main crystallization peak resembles that of LDPE, suggesting PE remains the dominant matrix

polymer in diaper C. However, in the case of diaper C, the presence of this additional thermal transition strongly implies a composite or blend structure, potentially combining PE with a non-PE reinforcing or nucleating agent. The second heating cycle (Figure 4.1b) further differentiates the samples. Diaper A displayed a broad melting endotherm between 90 and 125 °C, with two transitions that were not completely resolved, suggesting the melting of overlapping crystalline domains with varying lamellar thickness or perfection, again indicative of a multi-phase PE blend. Diapers B and C, by contrast, each showed a single dominant melting peak. Diaper B melted around 118 °C, which is typical of LDPE-rich materials, while the melting point of diaper C was slightly higher (~125 °C) and broad, due to a possible nucleating effect by the embedded secondary phase and thus increased crystallinity (higher melting enthalpy compared to diapers A and B, Table 4.1).

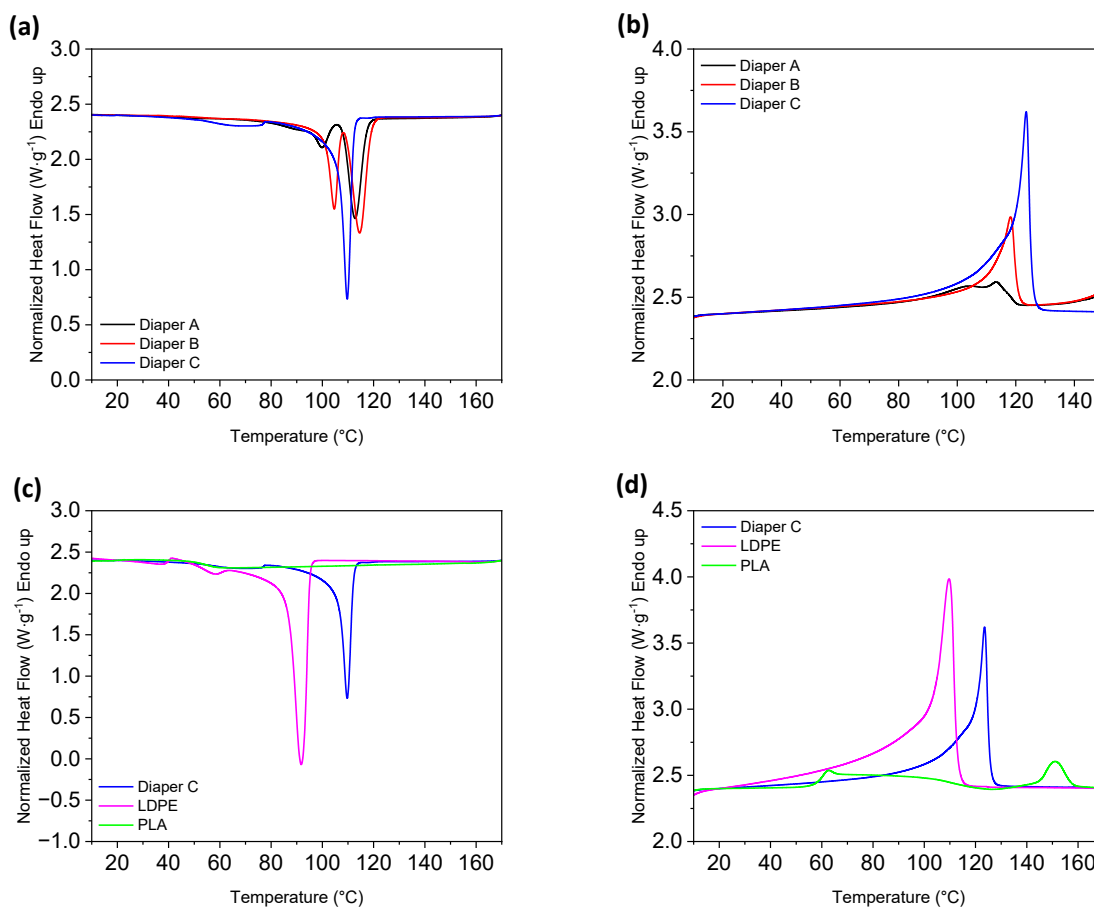


Figure 4.1. DSC cooling (a) and second heating (b) thermograms of diapers A, B and C backsheet samples. DSC cooling (c) and second heating (d) thermograms of diaper C, LDPE and PLA.

Table 4.1. Crystallization, melting and glass transition data for PLA, LDPE and diaper A, B and C.

Sample	$T_g / ^\circ\text{C}$	$\Delta C_p / \text{J} \cdot \text{g}^{-1}$	$T_{cc} / ^\circ\text{C}$	$\Delta H_{cc} / \text{J} \cdot \text{g}^{-1}$	$T_c / ^\circ\text{C}$	$\Delta H_c / \text{J} \cdot \text{g}^{-1}$	$T_m / ^\circ\text{C}$	$\Delta H_m / \text{J} \cdot \text{g}^{-1}$
Diaper A	-	-	-	-	100.2±0 ^a 112.8±0 ^b	4±0 ^a 30±0.6 ^b	113.5±0.12 ^a 158.2±0 ^b	13±1.5 ^a 22±0.6 ^b
Diaper B	-	-	-	-	104.6±1.7 ^a 114.7±0 ^b	14±0.6 ^a 33±1.2 ^b	118.4±1.7 ^a 159.4±0 ^b	19±0.6 ^a 25±0 ^b
Diaper C	-	-	-	-	109.8±0	44±1.7	123.4±0.35	52±0
LDPE	-	-	-	-	91.9±1.7	80±0	109±0	78±0
PLA	59.4±0.2	0.6±0.04	125.2±0.1	2±0.6	-	-	149.4±3.5	7±0.1

Physical quantities (i.e. temperature and enthalpy) associated with the first and second thermal transition. ΔH_c = crystallization enthalpy; ΔH_{cc} = cold crystallization enthalpy; T_c = crystallization temperature; T_{cc} = cold crystallization temperature; ΔH_m = melting enthalpy; T_m = melting temperature; T_g = glass transition temperature;

To explore the identity of the components in diaper C, its thermal behavior was compared with that of pure LDPE and PLA (Figures 1c and 1d, respectively). LDPE showed a typical crystallization peak near 95 °C and a melting point at 110 °C, consistent with previous reports, (Motlounge et al., 2017) reinforcing its presence in all three diaper backsheets. However, it is important to note that the crystallinities of all the diapers are lower than that of pure LDPE, suggesting the inclusion of plasticizers and/or additives during processing. PLA, on the other hand, displayed a clear glass transition temperature (T_g) at 65 °C, followed by a weak melting peak at 150 °C. This modest melting behavior is characteristic of semi-amorphous or processing-modified PLA, which can have reduced crystallinity due to rapid quenching or limited stereoregularity. The presence of a T_g in PLA, and the absence of the same in all diapers also indicates that PLA is not a constituent of the commercial samples tested. In summary, DSC results confirm that diapers A and B are composed of conventional PE blends, exhibiting characteristic dual crystallization and melting transitions. Diaper C shows unique thermal features, a broad melting peak at 125–130 °C and two crystallization

peaks at $-50\text{ }^{\circ}\text{C}$ and $-110\text{ }^{\circ}\text{C}$, indicating the presence of a PE-based composite structure, possibly containing cellulose based on the additional crystallization transition at $-50\text{ }^{\circ}\text{C}$ and literature reports linking similar DSC signatures to cellulose-PE composites.

TGA and derivative thermogravimetry (DTG) were used to evaluate the thermal stability, decomposition profile and composition of the diaper backsheet samples. TGA curves for diapers A, B and C are shown in Figure 4.2a, with corresponding DTG curves in Figure 4.2b. In addition, Figures 4.2c and 4.2d compare the thermal degradation behavior of diaper C with reference materials (i.e. LDPE, cellulose and PLA) to validate compositional inferences made from FTIR and SEM. Diapers A and B both exhibit two-stage degradation patterns, with initial mass loss occurring around $350\text{--}400\text{ }^{\circ}\text{C}$, followed by further decomposition near $470\text{--}500\text{ }^{\circ}\text{C}$. This behavior suggests that these diapers may contain more than one polymeric component, possibly due to surface coatings or adhesive layers commonly used in backsheet manufacturing. Their final degradation points indicate that both diapers are composed primarily of PE-based materials, but potentially with additional additives or surface treatments that affect their decomposition behavior. In contrast, diaper C displays a more distinct single-stage degradation, beginning at approximately $350\text{ }^{\circ}\text{C}$ and peaking around $470\text{ }^{\circ}\text{C}$, as seen in both the TGA and DTG curves. This degradation profile closely matches that of LDPE, confirming that the base polymer in diaper C is PE (Figure 4.2c). However, the onset of degradation is slightly earlier than that of pure LDPE, and the residue mass at $600\text{ }^{\circ}\text{C}$ is higher. These deviations are consistent with the presence of a second, more thermally labile phase, likely cellulose, as indicated by the FTIR and SEM results.

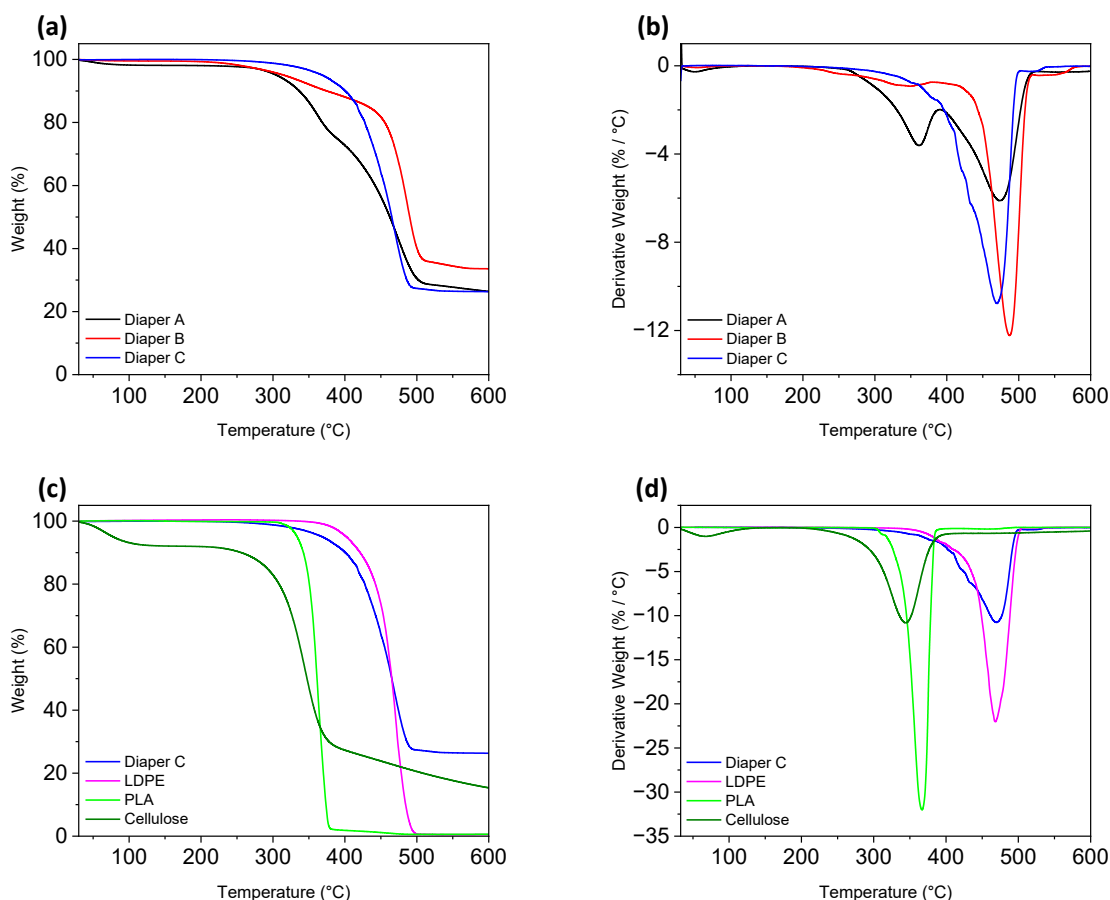


Figure 4.2. TGA (a) and DTG curves (b) of diapers A, B and C backsheet samples. TGA (c) and DTG curves (d) of diaper C, LDPE, PLA and cellulose.

To validate the composition of diaper C, its thermal profile was directly compared to that of LDPE, cellulose and PLA (Figures 4.2c and 4.2d). LDPE displayed a sharp, single-step degradation starting at $\sim 400^\circ\text{C}$ and peaking near 480°C , with minimal residue. PLA, in contrast, began degrading at a lower temperature ($\sim 280^\circ\text{C}$), with complete decomposition by 380°C and almost no residual mass, reflecting its known biodegradable nature and thermal instability at elevated temperatures. Cellulose showed earlier degradation onset ($\sim 280\text{--}350^\circ\text{C}$) and a multi-stage profile, consistent with depolymerization and oxidation reactions typical of natural fibers. Diaper C exhibited overlapping characteristics of both LDPE and cellulose: it began to degrade slightly earlier than LDPE and left behind a higher residue, which is likely due to the inorganic ash or char from cellulose and possible fillers. These observations support the notion that cellulose is present in diaper C as a discrete layer or

surface-adhered component, rather than being uniformly dispersed within the polymer matrix. In both cases, the interaction between the cellulose and the polymer is likely minimal, but the physical arrangement points to a laminated or adsorbed structure. The DTG curves further confirm these findings. Diaper C exhibits two overlapping peaks: a smaller one at $\sim 360\text{ }^{\circ}\text{C}$, corresponding to cellulose decomposition, and a dominant peak at $\sim 470\text{ }^{\circ}\text{C}$, corresponding to LDPE. LDPE shows a single major DTG peak, while cellulose presents an earlier, broad peak between $300\text{--}400\text{ }^{\circ}\text{C}$. PLA, again, displays a sharp, narrow DTG peak at $\sim 360\text{ }^{\circ}\text{C}$ and degrades completely.

FTIR was used to assess the molecular structure of the three diaper backsheet samples and to confirm the material composition observed in DSC. Figure 4.3a displays spectra for diapers A, B and C, while Figure 4.3b compares diaper C with reference polymers (i.e. LDPE, PLA) and cellulose. LDPE is chosen as a representative of the PE family, given that most manufacturers utilize such thermoplastics to make diaper backsheets (Uyanik and Kaynak, 2018). PLA was assessed to determine if any of the diaper backsheets used in this study is bio-based, in line with the goal of studying and evaluating its potential as an alternative to petroleum-based PE in current and future biodegradable diaper formulations (Roungpaisan et al., 2025). The inclusion of cellulose is based on the hypothesis of the presence of a fibrous polysaccharide-based material, as cellulose pulp has been previously used as part of diaper formulations (Espinosa-Valdemar et al., 2015; Płotka-Wasyłka et al., 2022). All diaper samples displayed broad bands near 3300 cm^{-1} , corresponding to O–H stretching, commonly attributed to moisture. Strong absorption bands between 2850 and 2950 cm^{-1} were observed in all diapers and in LDPE, confirming the presence of saturated aliphatic C–H bonds characteristic of PE (Figure 4.3a). These peaks were not as pronounced in PLA, as expected due to lack of long hydrocarbon chains (Figure 4.3b). In the $1500\text{--}1400\text{ cm}^{-1}$ region, all diaper samples showed distinct bending vibrations of CH_2/CH_3 groups, with diaper C showing the strongest intensity (Figure 4.3a). This region was also well-pronounced in LDPE but less so in PLA, suggesting that the diapers contain PE rather than PLA.

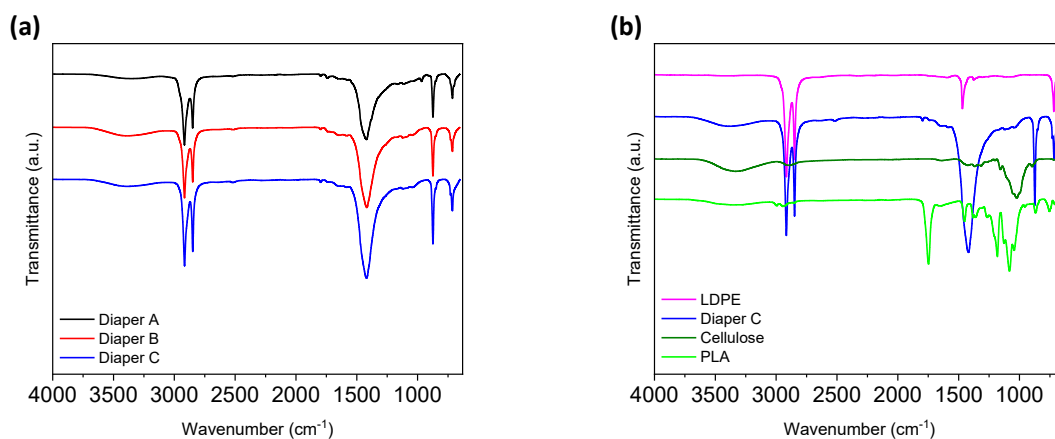


Figure 4.3. FTIR spectra of (a) diapers A, B and C backsheet samples and (b) diaper C, LDPE, PLA and cellulose.

In Figure 4.3b, PLA exhibited a strong and sharp peak at $\sim 1740\text{ cm}^{-1}$, attributed to C=O stretching in ester functional groups. This peak is not present in the spectra of all the diaper samples, conclusively demonstrating that PLA is not part of their composition. The lack of ester-based C=O signals in diapers and the strong presence of aliphatic features confirms they are PE-based. Lastly, the IR spectrum of cellulose is characterized by a broad O–H stretching band at 3330 cm^{-1} , due to the presence of hydrophilic hydroxyl groups. C–H stretching is observed at $2977\text{--}2892\text{ cm}^{-1}$, while the intense peak at $1000\text{--}1100\text{ cm}^{-1}$ is associated with C–O–C stretching and C–H rocking vibrations of the pyranose ring (Sikhosana, 2023; Motloun, 2024). Interestingly, all the IR vibrations emanating from the cellulose structure are observed, albeit to varying degrees, in the IR spectrum of diaper C (Figure 4.3b).

SEM was used to evaluate the morphological composition of diaper C in comparison with LDPE and PLA. It was further used to evaluate changes that took place after biodegradation of these samples. This technique was important for understanding microstructural interactions, especially the hypothesis of the presence of a polysaccharide-based natural fibre, most likely cellulose, on the polymer surface, as suggested by FTIR and TGA results. Figure 4.4 presents SEM micrographs of all three samples before and after biodegradation.

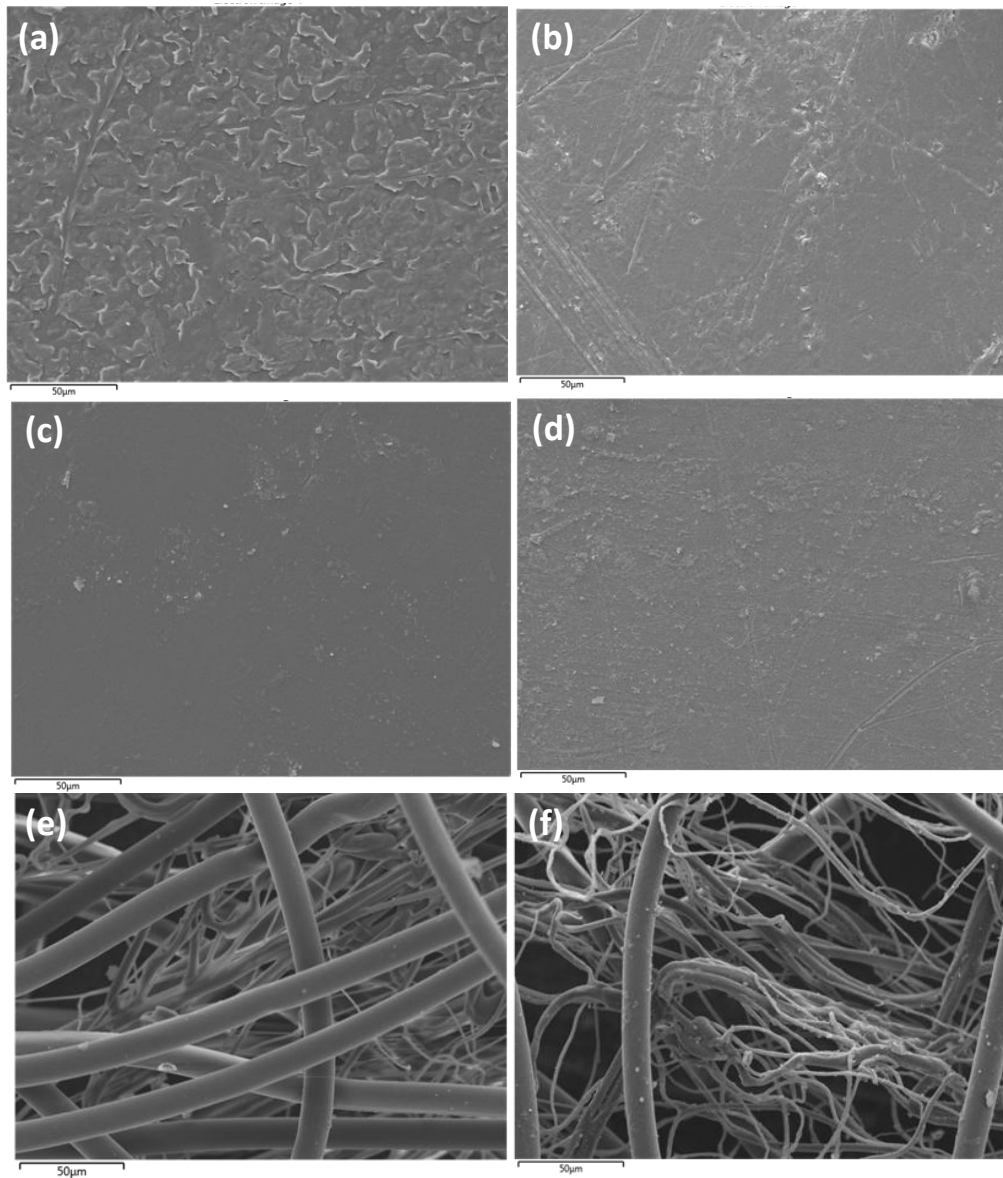


Figure 4.4. SEM micrographs of LDPE, PLA and diaper C samples before (a, c, e) and after biodegradation (b, d, f), respectively.

Diaper C reveals a heterogeneous fibrous morphology, consisting of inter-connected cylindrical fibers with varying thickness before biodegradation (Figure 4.4e). The thick fibers appear smooth and are typical of PE films, while the thin, loosely arranged fibers are consistent with cellulose fluff or superabsorbent polymer structures commonly found in diaper cores (Ajmeri and Ajmeri, 2010). Unlike the smooth and more compact surface observed in LDPE (Figure 4.4a), the surface of diaper C is more textured and irregular, suggesting that cellulose has adsorbed onto or fused with the polymer matrix, without

forming a homogeneous blend. This supports the observations from FTIR, where O–H and C–O–C stretching peaks were visible in diaper C but were not present in LDPE. The observed morphology after biodegradation shows slight changes in the diaper C backsheet sample, while both PLA and LDPE largely remain intact. A change in the morphology of the fibres in diaper C is noticeable. SEM images post-biodegradation exhibited rough, corroded and thinner fibres (Figure 4.4f) in contrast to the initially intact and smooth fibres observed before biodegradation. This suggests that the cellulose infused in the diaper increased the hydrophilicity of the material, which is suitable for biodegradation, allowing for structural weakening and fragmentation (Zambrano et al., 2020). No visible morphological changes were observed in LDPE after the biodegradation test (Figure 4.4b), as the polymer remained intact with no significant erosion or cracks. This is due to its resistance to hydrolysis and biodegradation which is attributed to its hydrophobic carbon backbone and large molecular weight (Zambrano et al., 2020). This is also supported by biodegradation test results where the initial weight of the sample did not decline over time. For PLA, only minor morphological changes were observed after the biodegradation test compared to the starting sample (Figures 4.4c and 4.4d), despite the polymer being classified as biodegradable. This is further supported by a very small weight loss recorded during the biodegradation test, and it suggests that the hydrolytic degradation that occurred was insufficient. According to Mistry et al. (2023), PLA degrades effectively under industrial composting conditions characterized by sustained high temperatures which are challenging to maintain under non-industrial composting conditions. Although these outcomes are evidence of PLA biodegradability, they emphasize its dependence on industrial composting for efficient and rapid biodegradation. The observed morphology in SEM supports the idea that cellulose fibers possibly act as heterogeneous nucleating agents, changing the thermal crystallization behavior the polymer, giving rise to higher melting enthalpies. In addition, the rough surface of diaper C could increase hydrophilicity and thus biodegradation potential, aligning with the broader study aim of evaluating materials for eco-friendly backsheet alternatives.

Biodegradation studies were conducted in accordance with the Standard Test Method for Determining Weight Loss from Plastic Materials Exposed to Simulated Municipal Solid-Waste (MSW) Aerobic Compost Environment (ASTM D6003-96), using a stainless-steel

container filled with organic compost. The compost was packed to a depth of 2 cm from the bottom, then diaper C, LDPE and PLA samples were placed on top of the compost with sufficient spacing in-between to ensure uniform degradation (Figure 4.5a). Subsequently, the three samples were covered with additional compost until the container was completely filled, with the depth of the samples from the top surface measured at 3 cm (Figure 5b). The container was stored at room temperature and the compost moisture was maintained by regularly sprinkling distilled water, as per the manufacturer’s instructions.

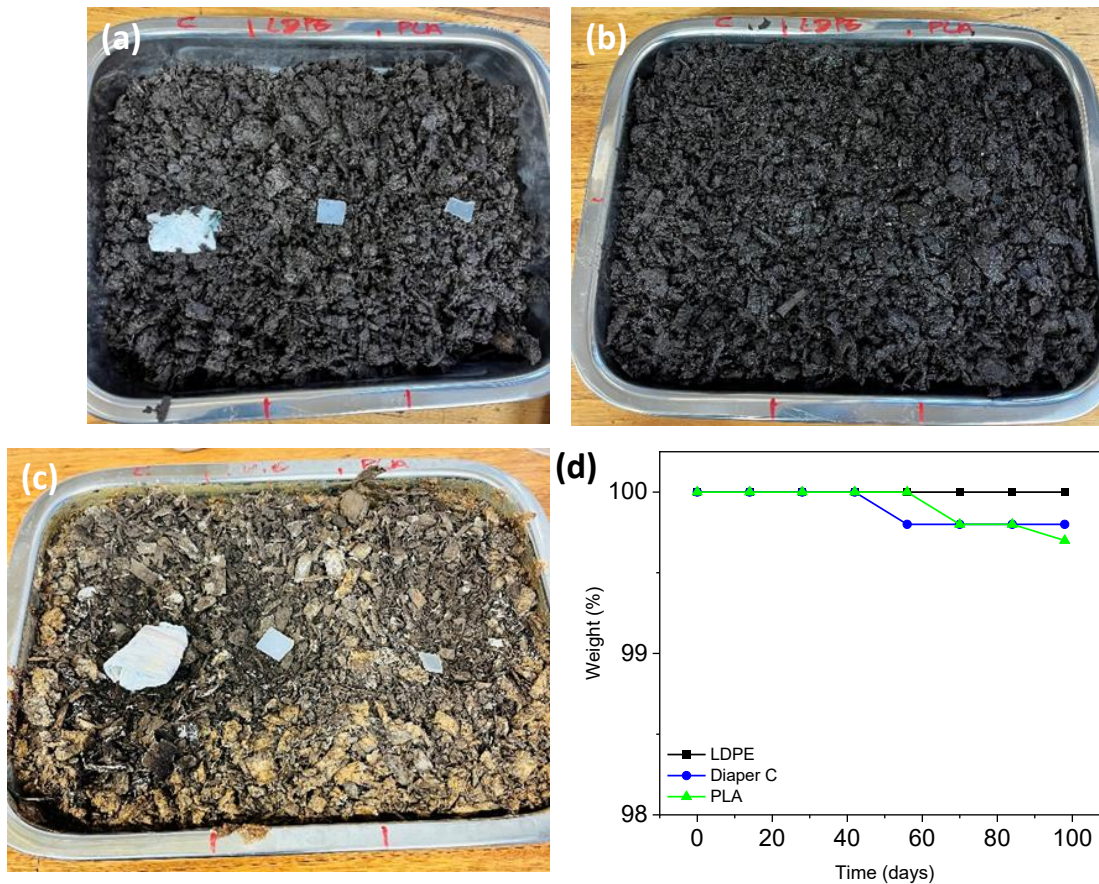


Figure 4.5. Test samples (a) before and (b) after being fully covered with organic compost. (c) Test samples after a 90-day soil burial test. (d) Biodegradation performance of diaper C, LDPE and PLA over time in an organic compost environment.

Figure 4.5d displays the biodegradation performance of the three samples over a 98-day period. Consistent with results from other techniques, diaper C is confirmed to be composed of LDPE with cellulose infusion. The observed weight loss in diaper C beginning on day 42,

which occurs earlier than PLA, is attributed to the degradation of part of the cellulose component. This is consistent with the findings of Brunšek et al. (2023), who reported that cellulose typically degrades before PLA under soil burial conditions. However, the residual weight of diaper C remained unchanged beyond the partial degradation of cellulose, indicating that the remaining component is LDPE, a non-biodegradable polymer, and a small amount of cellulose. This reinforces the need for replacing LDPE in diaper backsheets with more environmentally responsible materials. PLA showed partial degradation beginning on day 56, with continued weight loss until the end of the test. Although the observed weight loss was minimal, and lower than the values reported by Yagi et al. (2009), Arrieta et al. (2014) and Boonmee et al. (2016), this discrepancy may be due to factors such as low microbial activity, reduced moisture retention in the compost, or the difference in the thicknesses and crystallinities of the used PLA films. Despite the slow degradation, these findings confirm that PLA is indeed biodegradable under soil burial conditions. Furthermore, it is anticipated that the use of thinner PLA films in commercial diaper manufacturing would result in a significantly faster degradation rates. As expected, LDPE did not show any mass loss under the composting conditions due to its non-biodegradable nature. The final (visual) inspection on day 98 (i.e. post-burial) showed little morphological changes in the LDPE and PLA samples, while the cellulose-rich layer in diaper C had mostly degraded (Figure 4.4c).

The inclusion of biodegradable polymers such as PLA in diaper backsheets holds a clear potential to enhance environmental sustainability. However, the complete adoption of PLA-based disposal diapers depends on a few factors: PLA has relatively low crystallinity and thus low thermal stability, which is disadvantageous during high-temperature processing (i.e. during manufacturing). In addition, the polymer is prone to brittle fracture, and thus cannot be employed in applications where high mechanical performance is a requirement (i.e. the diaper backsheet should be able to withstand impact forces and also bend without breaking). It has been shown in literature that through nucleation and reinforcement, the incorporation of bio-based nanofillers can significantly increase the crystallinity and thermal stability of PLA (Ngwenya et al., 2025). Furthermore, the brittle nature of the polymer can be overcome through blending with more ductile polymers, such as poly(ϵ -caprolactone), giving

rise to materials with improved impact resistance (Fernández-Tena et al., 2023). Although results showed slower-than-expected biodegradation rates under the applied test conditions, the use of fillers such as cellulose have shown that the rate of biodegradation could be accelerated (Kalita et al., 2020). Therefore, of the various biodegradable polymers currently in the market, PLA remains the most cost-effective and promising candidate for replacing the PE family in single-use diaper products.

4.4 Conclusions

This work presented a systematic analysis of three commercial diaper backsheets and also evaluated the suitability of PLA as a biodegradable alternative to petroleum-based PE. DSC showed that diaper C differs from diapers A and B in its crystallization and melting behavior, recording the highest melting enthalpy of the three diapers, possibly due to nucleation effects by the infused cellulose. The presence of cellulose was confirmed by FTIR, which identified O–H and C–O–C functional groups characteristic of cellulose, and by SEM, where fibrous structures, typical of cellulose fibres, were observed. TGA further demonstrated that diaper C, despite containing cellulose, retains the thermal degradation behavior of typical PE materials, with major decomposition occurring above 450 °C. The adsorbed cellulose slightly lowers the onset of degradation and increases residual mass but does not substantially enhance biodegradability, possibly due to insufficient amounts within the material. FTIR and TGA comparisons with PLA confirmed that the thermal behavior of PLA and complete degradation at lower temperatures (-360 °C) reinforce its role as a promising biodegradable reference polymer. Biodegradation testing over a 98-day period revealed that diaper C exhibited earlier signs of weight loss (from day 42), attributed to the partial degradation of the cellulose fraction, consistent with literature reporting that cellulose degrades before PLA under soil burial conditions. However, the remaining LDPE-based component of diaper C showed no further weight change, confirming its non-biodegradable nature. In contrast, PLA began degrading from day 56 and continued to lose mass over time, albeit at a slower rate relative to prior studies. Factors such as limited microbial activity, moisture content, crystallinity and film thickness may explain the slower biodegradation rate. Nonetheless, the test confirms that PLA is biodegradable under composting conditions and is likely to degrade faster in commercial applications using thinner films. Collectively, the findings show that

while cellulose-infused PE back sheet materials such as diaper C represent a step toward sustainability, they fall short of fully addressing the environmental burden posed by traditional diapers. The limited biodegradation of diaper C underscores the need for a complete material substitution rather than partial modification. Replacing PE with PLA-based composites offers a more viable route toward achieving significant environmental benefits in single-use hygiene products without compromising structural integrity.

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Conflict of interest

The authors declare no conflict of interest.

Ethical approval

Not applicable.

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Chapter 5

Conclusions

This dissertation investigated the environmental implications of current disposable diaper materials and evaluated biodegradable alternatives. The focus was on PLA as a sustainable substitute for PE in diaper backsheet layers. Through a two-pronged approach – first, a review of the global landscape of biodegradable polymers in diaper applications (Article 1), and second, an in-depth experimental characterisation and biodegradation assessment of commercial diaper backsheets (Article 2) – the study offered both theoretical and practical insights into material sustainability in single-use hygiene products.

The findings showed the urgent need to replace conventional, non-biodegradable polymers such as LDPE with alternatives that align with the goals of sustainable development. Article 1 highlighted that while LDPE offers mechanical advantages, its long environmental persistence and non-compostable nature make it increasingly untenable in light of growing waste burdens. PLA emerged as a leading candidate among biodegradable polymers due to its favourable environmental profile, cost-effectiveness, and commercial availability. Although inherently more brittle, its performance limitations can be overcome through blending or plasticisation, making it a realistic option for industrial-scale implementation.

Article 2 built upon this foundation by experimentally characterising the thermal, structural, and morphological properties of three commercial diaper backsheets. Diaper C, which included cellulose components, exhibited unique thermal and surface characteristics not found in the LDPE-only samples (Diapers A and B). However, despite these modifications, Diaper C retained the core degradation profile of LDPE, revealing that the mere inclusion of biodegradable fillers, such as cellulose, does not translate into significant improvements in environmental performance. Biodegradation testing confirmed this: while the cellulose fraction of Diaper C degraded early, the LDPE matrix remained intact. In contrast, PLA demonstrated observable, albeit slower, mass loss under composting conditions, validating its classification as a biodegradable polymer and reaffirming its potential in backsheet applications.

Together, these findings showed that a partial substitution strategy, such as blending LDPE with cellulose, offered limited environmental gains. A full material transition to PLA or other biodegradable polymers, supported by advances in formulation and processing, is essential for meaningful environmental impact. Importantly, material substitution alone is not sufficient. Broader systemic changes, including regulatory frameworks, market incentives, and public education, are necessary to support a shift toward sustainable diaper manufacturing, particularly in regions with inadequate waste management infrastructure.

In conclusion, this dissertation advances the scientific understanding of biodegradable polymer performance in diaper applications and contributes valuable evidence in favour of PLA as a feasible and impactful alternative to PE. By combining literature-based analysis with experimental validation, the study provides a strong foundation for future research, product innovation, and policy development aimed at reducing the ecological footprint of disposable hygiene products.