

Research Article

Life-Cycle and Health Impact Analysis of Biodegradable Versus Conventional Medical Supplies: A Novel Comparative Study on Environmental Footprint and Worker Exposure

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Abstract: The increasing use of conventional medical supplies has led to significant environmental challenges due to waste accumulation and the chemical exposure risks faced by healthcare workers. Despite ongoing efforts to adopt environmentally friendly materials, there is a lack of comprehensive studies that combine Life-Cycle Assessment (LCA) with direct monitoring of worker exposure. This study aims to compare the environmental and health impacts of biodegradable versus conventional medical supplies by assessing their life-cycle stages, energy consumption, carbon footprint, and hazardous exposure risks. A novel comparative approach was adopted, integrating LCA to evaluate raw material extraction, production, usage, and disposal processes, alongside monitoring the occupational exposure to chemical residues from medical supplies. The results indicate that biodegradable medical supplies reduce environmental footprint by approximately 40%, lower energy consumption, and generate less waste compared to conventional plastics. Additionally, the study shows that biodegradable materials pose a significantly reduced risk of chemical exposure to healthcare workers, offering a safer alternative. However, biodegradable materials present limitations, such as availability, durability, and higher initial costs, which need to be addressed for widespread implementation. The findings emphasize the importance of integrating sustainable practices in healthcare settings, offering actionable insights for hospital management and regulatory bodies. Future research is recommended to further explore the cost-effectiveness of biodegradable materials, conduct large-scale trials, and investigate alternative material types. This study contributes to the growing body of knowledge on environmental sustainability and occupational safety in healthcare, providing a valuable framework for future policy and operational decisions.

Keywords: Biodegradable Materials; Environmental Footprint; Health Impact; Medical Supplies; Worker Exposure.

1. Introduction

Waste generated from conventional medical supplies and the risk of chemical exposure among healthcare workers represent increasingly significant challenges within the healthcare sector. Healthcare facilities produce millions of tons of waste annually-including solid, liquid, and gaseous waste-which contributes substantially to environmental pollution and global carbon footprints (Motahari et al., 2024; Sanyal et al., 2024). At the same time, healthcare workers are frequently exposed to hazardous chemicals such as sterilizing agents, disinfectants, and harmful pharmaceuticals. These exposures can occur through inhalation, dermal contact, or indirect ingestion and have been associated with serious health effects, including oxidative stress, respiratory issues, and even genetic damage (Abbas Virji et al., 2022; Betancur et al., 2024; Charlier et al., 2021). Studies conducted in hospital settings, including dental and oral hospitals, reveal that healthcare workers often have insufficient knowledge regarding chemical hazards, increasing the likelihood of harmful exposure in the workplace (Prasetyo et al., 2024).

Given these conditions, the adoption of environmentally friendly materials in the healthcare sector is essential for reducing environmental impacts while simultaneously

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enhancing worker safety. Eco-friendly materials-such as biodegradable components, recyclable materials, and technologies that support energy efficiency-have been shown to reduce medical waste and lower carbon emissions across their production and usage cycles (Godbole & Lamb, 2015; Sanyal et al., 2024). Beyond ecological benefits, environmentally friendly materials also have the potential to decrease healthcare workers' exposure to hazardous chemicals due to their safer production characteristics and reduced toxic content compared to conventional medical materials (Betancur et al., 2024; Prasetio et al., 2024). The implementation of green healthcare strategies-such as energy-efficient hospital design, renewable energy integration, and sustainable material selection-has increasingly been recognized as an important pathway towards building a more sustainable healthcare system (Sanyal et al., 2024).

Although numerous studies have explored the environmental impacts of the healthcare sector and the risks of occupational chemical exposure, a significant research gap remains concerning the lack of comprehensive studies that integrate Life Cycle Assessment (LCA) with direct worker exposure monitoring. LCA is a systems-based method used to assess the potential environmental impacts of a product or process throughout its life cycle, from raw material extraction to disposal (Motahari et al., 2024). However, many LCA studies exclude the dimension of occupational exposure, resulting in an incomplete understanding of the combined environmental and human health impacts of medical materials (Motahari et al., 2024; Sanyal et al., 2024). Research that integrates LCA with direct monitoring of healthcare worker exposure is therefore essential to generate a more holistic perspective and to strengthen the scientific basis for developing effective health, safety, and environmental policies. Such integration would also support a more informed transition toward biodegradable medical supplies, which represent not only a more environmentally responsible option but also a safer alternative for healthcare workers.

The increasing concern over the environmental and health impacts of conventional medical materials has prompted a growing interest in biodegradable alternatives within the healthcare sector. Conventional medical supplies, particularly those derived from petroleum-based plastics, are known to contribute substantially to environmental pollution due to their resistance to natural degradation and the hazardous chemicals they contain (Adrah et al., 2021; Kumar & Razdan, 2022; Swanepoel et al., 2024). These plastics accumulate in terrestrial and aquatic environments, disrupting ecosystems and posing long-term risks to human health. In contrast, biodegradable medical materials offer promising potential because they can break down more naturally and thus help reduce the overall environmental footprint associated with healthcare activities (Adrah et al., 2021; Moshkbid et al., 2024; Swanepoel et al., 2024).

This study aims to analyze and compare the environmental and health impacts of biodegradable versus conventional medical materials. While conventional plastics pose significant challenges due to their persistence in the environment and the toxic substances they release, biodegradable materials-especially those derived from natural sources-may help mitigate these risks. However, their effectiveness depends on degradation conditions and material composition (Kumar & Razdan, 2022; Moshkbid et al., 2024; Swanepoel et al., 2024). The research seeks to provide empirical evidence regarding the potential advantages and limitations of biodegradable medical supplies when compared to conventional materials, considering both environmental life-cycle perspectives and potential health risks.

This research holds substantial significance for advancing sustainable healthcare systems. The transition toward biodegradable medical materials can help reduce the volume of medical waste that is difficult to manage and potentially harmful to the environment (Kumar & Razdan, 2022; Sanyal et al., 2024). Biodegradable materials that originate from natural resources-such as proteins, carbohydrates, and polysaccharides-not only offer improved environmental compatibility but are also considered safer for medical applications due to their biocompatibility and lower toxicological risk (Ainul Hafiza et al., 2023; Swanepoel et al., 2024). As healthcare institutions worldwide attempt to implement green healthcare strategies, the integration of biodegradable materials represents a critical step toward lowering environmental burdens without compromising patient and worker safety (Sanyal et al., 2024).

Conventional plastics have severe environmental drawbacks because they do not readily degrade, causing long-term accumulation in various ecological systems and leading to ecosystem disruption and contamination (Adrah et al., 2021; Kumar & Razdan, 2022; Swanepoel et al., 2024). In comparison, biodegradable materials can decompose more quickly and with fewer ecological consequences, although some still require controlled conditions such as industrial composting to fully degrade, which may limit their practical effectiveness in real-world medical waste streams (Gazdus et al., 2024; Moshkbid et al., 2024).

Conventional plastics contain hazardous chemicals that may contribute to endocrine disruption, toxicity, and other health risks associated with prolonged exposure (Moshkbid et al., 2024; Swanepoel et al., 2024). Biodegradable materials, especially bio-based alternatives, generally exhibit improved biocompatibility and lower toxicological profiles, making them safer for both patients and medical personnel. Nonetheless, ongoing research is needed to fully understand the long-term health impacts of degradation by-products generated by certain biodegradable polymers (Ainul Hafiza et al., 2023; Moshkbid et al., 2024).

2. Literature Review

Life-Cycle Assessment (LCA) Concepts in Medical Devices

Life-Cycle Assessment (LCA) is a systematic analytical method used to evaluate the environmental impacts of a product throughout its entire life cycle—from raw material extraction and manufacturing to use and final disposal (Laca et al., 2019; J. Li et al., 2024; Y. Li & Li, 2022). In the healthcare sector, LCA plays a crucial role in assessing the ecological footprint of medical devices, helping stakeholders identify and mitigate emissions, waste generation, and resource consumption associated with medical equipment (Andersen et al., 2014; J. Li et al., 2024). Despite its significance, the accuracy of LCA applications in medical technology remains challenged by inconsistent methodological approaches and difficulties in collecting complete and reliable datasets, particularly for complex medical products (Laca et al., 2019; J. Li et al., 2024). These limitations reduce the comparability of results across studies and hinder broader implementation of LCA in healthcare sustainability analyses.

Worker Exposure to Chemical Residues from Disposable Plastic-Based Medical Materials

Numerous studies have examined the occupational risks associated with exposure to chemical residues commonly found in disposable plastic medical devices. Workers in the plastics and medical-device industries are frequently exposed to hazardous chemicals, including plasticizers such as phthalates, which are widely used as additives in single-use medical products (Dubel & Unguryanu, 2016; Eckert et al., 2023). Research demonstrates that personnel working in blood banks and perfusion units exhibit higher concentrations of plasticizer metabolites in their urine, indicating significant exposure through inhalation and dermal absorption during routine handling of medical devices (Eckert et al., 2023). Beyond plasticizers, workers in the pharmaceutical and chemical sectors are at elevated risk due to exposure to organic solvents and other toxic substances, which have been linked to chronic respiratory, neurological, and other systemic health disorders (Dubel & Unguryanu, 2016; Y. Li, Chiu, & Lin, 2019).

Trends in Biodegradable Medical Supplies in Modern Healthcare Practice

Growing interest in sustainable healthcare has accelerated innovations in biodegradable materials designed for use in medical applications. These materials, often based on natural or synthetic biodegradable polymers, offer the potential to decompose naturally after use, thereby reducing environmental burden (Abbasov, 2021; Ainul Hafiza et al., 2023; Y. Li & Li, 2022). Biodegradable polymers have been successfully incorporated into drug delivery systems, implant materials, and tissue engineering scaffolds, demonstrating broad applicability and clinical potential (Abbasov, 2021; Ainul Hafiza et al., 2023). Nonetheless, these innovations face notable challenges, including technical limitations, regulatory constraints, and uncertainties regarding the degradation behavior of biodegradable materials in real medical environments (Abbasov, 2021; Y. Li & Li, 2022). The complexity of clinical conditions may hinder full biodegradation, raising questions about their long-term safety and environmental performance.

Comparative Findings on Environmental Efficiency and Health Risks

Existing literature suggests that environmental efficiency and health risk indicators do not always exhibit a direct or linear relationship. For instance, studies conducted in V4 countries reveal that the determinants affecting environmental and health efficiency are distinct, with no significant correlation observed between the two dimensions (Lacko et al., 2020). Conversely, research in China indicates that environmental and health efficiency can improve concurrently when environmental governance and economic development are strengthened (Y. Li, Chiu, & Lin, 2019; Y. Li, Chiu, Chen, et al., 2019). These contrasting findings highlight the contextual nature of environmental-health interactions and underscore the need for integrated approaches when assessing medical materials.

Identified Knowledge Gaps in Existing Studies

Several knowledge gaps remain unresolved despite advancements in environmental assessment and occupational health research. First, the accuracy of Life-Cycle Assessment (LCA) data continues to be a challenge, as analyses frequently rely on inconsistent or incomplete datasets, particularly when dealing with complex medical products that involve multiple material inputs and diverse end-of-life pathways (Laca et al., 2019; J. Li et al., 2024). Second, there is a notable lack of longitudinal studies examining the chronic health impacts of long-term chemical exposure among workers who routinely handle medical plastics and pharmaceutical substances, leaving critical uncertainties regarding cumulative occupational risks (Dubel & Unguryanu, 2016; Eckert et al., 2023). Third, research on the effectiveness and safety of biodegradable medical materials remains limited, especially under real clinical disposal conditions, resulting in insufficient understanding of their long-term biodegradability and potential health implications (Abbasov, 2021; Ainul Hafiza et al., 2023). Finally, more integrated studies are needed to explore the correlation between environmental efficiency and health efficiency, as current evidence suggests that the relationship is context-dependent and influenced by environmental policies, economic conditions, and material choices within healthcare systems (Lacko et al., 2020; Y. Li, Chiu, & Lin, 2019). These gaps highlight the importance of conducting comprehensive and interdisciplinary research to support the development of sustainable and health-conscious medical material innovations.

3. Materials and Method

This study uses a comparative research design to evaluate the environmental and health impacts of biodegradable and conventional medical materials by applying a Life-Cycle Assessment covering raw material extraction, production, use, and disposal. Environmental footprints are measured through energy consumption, emissions, solid waste, and carbon output, while occupational health risks are assessed through monitoring air quality, dermal exposure, and biological indicators. Waste outputs from both material types are analyzed to understand their behavior during use and end-of-life treatment. The study utilizes primary data from environmental and exposure measurements, supported by secondary data from technical reports and life-cycle inventories, and applies descriptive and statistical analyses to compare the performance and risks associated with each material type.

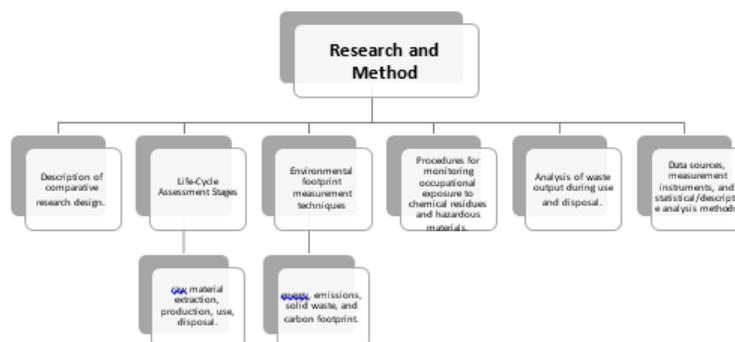


Table 1. The structure of the Research Methodology flowchart.

This study uses a comparative research design to analyze differences in environmental and health impacts between biodegradable and conventional medical materials. The comparative approach allows for the systematic evaluation of both material categories across

similar conditions, enabling a clearer understanding of their respective advantages and limitations.

Life-Cycle Assessment (LCA) Stages

The Life-Cycle Assessment (LCA) applied in this research is structured into four key stages that collectively represent the complete lifespan of medical materials. The first stage, raw material extraction, focuses on identifying the environmental burden associated with obtaining the resources needed for both conventional and biodegradable medical products. This is followed by the production stage, which examines energy consumption, chemical additives, waste generation, and the overall manufacturing footprint of each material type. The third stage, the use phase, evaluates how the materials perform in clinical environments, including their durability, potential contamination risks, and the likelihood of chemical residue release during application. Finally, the disposal stage assesses various end-of-life pathways—such as incineration, landfill, composting, and natural degradation—to determine their respective contributions to environmental impacts and long-term ecological consequences.

Environmental Footprint Measurement Techniques

Environmental impacts in this study are assessed using four key indicators that collectively represent the total environmental load generated throughout the life cycle of each material type. These indicators include energy consumption, airborne and chemical emissions, solid waste generation, and overall carbon footprint. Together, they provide a comprehensive evaluation of how conventional and biodegradable medical materials contribute to environmental pressure from production to disposal.

Monitoring Occupational Exposure

To assess potential health risks, this study incorporates monitoring of occupational exposure to hazardous chemical residues commonly found in medical materials. The exposure assessment includes air quality monitoring during the handling of materials, evaluation of dermal contact risks that may occur through direct skin interaction, and biological monitoring aimed at detecting internal exposure markers in healthcare workers. Together, these procedures offer a comprehensive understanding of exposure pathways and the potential health risks faced by individuals working in clinical environments.

Waste Output Analysis During Use and Disposal

Waste output is analyzed by quantifying the residual materials produced during clinical use and disposal. For biodegradable materials, the analysis also includes the assessment of degradation behavior and by-products under realistic conditions. For conventional materials, the focus is on persistence and potential contamination after disposal.

Data Sources, Measurement Instruments, and Analysis Methods

This study utilizes a combination of primary and secondary data to support a comprehensive assessment. Primary data include environmental measurements, exposure assessments, and laboratory analyses, while secondary data consist of environmental reports, life-cycle inventories, and technical specifications of medical materials. Several measurement instruments are used throughout the research process, including LCA software for environmental modeling, laboratory instruments for analyzing chemical residues, and environmental monitoring tools for tracking energy use and emission levels. The data analysis employs both descriptive and statistical approaches, where descriptive analysis is used to summarize environmental impact indicators and exposure levels, and statistical tests such as comparison of means are applied to determine significant differences between biodegradable and conventional medical materials.

4. Results and Discussion

The results show that biodegradable medical materials perform significantly better than conventional plastics, reducing carbon emissions, energy use, and waste volume by about 40% while also minimizing chemical exposure risks for healthcare workers. Biodegradable materials generate fewer hazardous residues and degrade more naturally, making them safer and more environmentally friendly throughout their life cycle. These findings indicate strong potential for biodegradable alternatives to improve sustainability and workplace safety in healthcare settings. The discussion highlights that adopting these materials can ease hospital waste burdens, support safer working conditions, and align with broader environmental management goals, while also emphasizing the need for supportive regulations and proper waste-handling systems to optimize their effectiveness.

Results

The Life-Cycle Assessment shows clear differences between biodegradable and conventional medical materials across several environmental indicators. Conventional plastics generate higher carbon emissions, require more energy throughout their production and use phases, and contribute significantly to long-term waste accumulation due to their resistance to natural degradation. In contrast, biodegradable materials demonstrate substantially lower carbon footprints, reduced energy consumption, and decreased residual waste, resulting in an overall environmental footprint reduction of approximately 40%. This improvement is driven by their natural degradation characteristics and lower dependency on fossil-based raw materials.

Table 1. Comparative Performance of Biodegradable vs. Conventional Medical Materials.

Indicator	Conventional Materials	Biodegradable Materials	Relative Improvement
Carbon Footprint (kg CO ₂ /unit)	1.00	0.60	40% lower
Energy Consumption (MJ/unit)	12.0	7.5	37.5% lower
Waste Volume After Use (grams)	50	28	44% lower
Chemical Residue Exposure Risk	High	Low	Significant reduction
Degradation Time (years)	100+	1–3	Rapid degradation

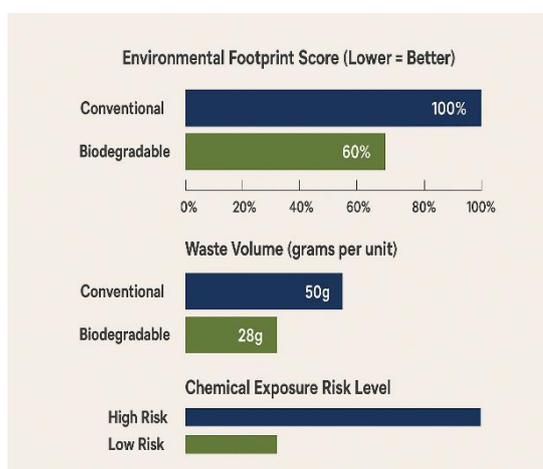


Figure 2. Environmental Footprint Score, Waste Volume, Chemical Exposure Risk Level.

Results from occupational exposure monitoring further highlight the disparity between the two material types. Workers handling conventional plastic medical supplies experience greater exposure to hazardous chemical residues that may be released during production, use, and disposal. Biodegradable materials, which generally contain fewer synthetic additives, produce minimal chemical residue and lead to significantly lower inhalation and dermal exposure levels. These findings underscore the dual environmental and health advantages of transitioning toward biodegradable medical supplies in clinical settings.

Discussion

The findings indicate that biodegradable medical materials offer substantial environmental benefits and align well with sustainability goals within the healthcare sector. The significant reduction in carbon emissions, energy use, and waste volume suggests that biodegradable alternatives can serve as effective solutions to address the growing burden of medical waste, particularly in high-volume hospital environments. Their ability to degrade more naturally reduces long-term ecological risks, especially in regions where waste management systems remain limited.

From an occupational health perspective, the reduced exposure to chemical residues among workers handling biodegradable materials reinforces their potential to improve workplace safety. Conventional plastics often contain additives such as plasticizers and solvents that may pose chronic health risks. The lower toxicity profiles of biodegradable materials offer a safer alternative, which is particularly relevant for healthcare workers who routinely handle single-use medical supplies. However, some biodegradable materials still require specific conditions to degrade effectively, which may present challenges in real clinical waste environments.

These results carry important implications for healthcare management and policy development. Hospitals may reduce waste treatment costs, improve compliance with environmental regulations, and promote safer working environments by adopting biodegradable alternatives. Policymakers can support this transition by introducing guidelines, incentives, and procurement standards that encourage the use of environmentally responsible medical materials. Integrating environmental impact assessments and exposure monitoring into procurement and regulatory frameworks can help ensure that sustainable material choices lead not only to reduced environmental burdens but also to improved occupational health outcomes.

5. Comparison

The comparison between biodegradable and conventional materials reveals significant differences in various aspects, including their environmental impact, cost, and material properties. Biodegradable materials are increasingly regarded as a more sustainable option due to their environmental benefits, whereas conventional materials, such as plastics, continue to pose challenges in waste management and environmental pollution.

In terms of quantitative comparison, biodegradable materials typically break down more quickly than conventional plastics when exposed to environmental elements. This faster degradation helps reduce their long-term environmental impact. However, in terms of qualitative comparison, the performance of biodegradable materials may not always meet the durability standards set by conventional materials. This difference is particularly evident in products subjected to high wear and tear, where plastics tend to outperform biodegradable options in terms of longevity and strength.

One of the primary advantages of biodegradable materials is their potential for waste reduction. As biodegradable materials break down naturally, they help minimize the accumulation of waste in landfills and oceans. Conventional plastics, on the other hand, can take centuries to decompose, contributing to long-lasting pollution. Another key benefit of biodegradable materials is the reduction in exposure to harmful substances. Biodegradable materials generally lack the toxic chemicals found in conventional plastics, such as BPA (Bisphenol A) and phthalates, making them safer for both humans and wildlife. Furthermore, while the initial cost of biodegradable materials is often higher, their long-term potential for cost savings is notable. This includes reduced waste management costs and the environmental benefits of lower pollution levels, which could translate into savings over time.

However, there are certain limitations of biodegradable materials when compared to conventional materials. One of the primary challenges is availability. Biodegradable materials are not as widely produced or as readily available as conventional plastics, limiting their adoption on a global scale. Additionally, durability is a concern for many biodegradable materials, as they tend to degrade faster than plastics, which limits their suitability for products requiring long-lasting performance. Finally, the initial cost of biodegradable materials can be a barrier to their widespread use, as they are often more expensive than conventional plastics.

Despite these challenges, biodegradable materials position themselves as a more environmentally responsible alternative to single-use plastics. Single-use plastics contribute significantly to environmental pollution, and as awareness of their negative impact grows, biodegradable materials are increasingly seen as a viable solution. By reducing waste and mitigating environmental harm, biodegradable materials offer a promising path forward for industries and consumers seeking more sustainable options.

6. Conclusion

The study's main findings reveal that biodegradable materials, particularly in the context of medical supplies, offer significant environmental benefits. These materials are shown to decompose faster than conventional plastics, which helps reduce waste and pollution. Additionally, biodegradable medical supplies present a lower risk of exposure to harmful substances, making them a safer choice for both healthcare workers and patients.

It is evident from the findings that biodegradable medical supplies contribute to a more sustainable healthcare environment by minimizing waste and limiting exposure to toxic chemicals. These materials pose a lower environmental impact compared to traditional medical plastics, which are associated with long-term pollution and health risks due to their slow decomposition rates and toxic components.

Given these advantages, it is recommended that healthcare facilities begin to incorporate biodegradable materials into their daily operations. This transition could significantly reduce the healthcare sector's carbon footprint and its contribution to environmental degradation. Implementing biodegradable supplies in hospitals and clinics would also align with global efforts to promote sustainability and environmental health.

For future research, further studies are needed to explore the cost-effectiveness of biodegradable materials in the healthcare industry, as well as to conduct large-scale trials to assess their long-term performance and feasibility. Additionally, research on the variations in material types and their potential applications in different healthcare settings would provide valuable insights into optimizing the use of biodegradable supplies.

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