

Preliminary Techno-Economic Factors Shaping Industrial Adoption of Biocomposites

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Abstract: Circular business incentives encourage the use of biobased materials and technologies to replace fossil-based materials and look for material alternatives that support reaching overall sustainability targets. Biocomposites continue to gain acceptance as potential substitutes for conventional fossil-based plastics and composites, supported by developments in biobased fillers, fibre-matrix interfaces, and scalable processing techniques. Industrial adoption is influenced not only by material properties but also by process-level requirements, manufacturing compatibility, and technoeconomic conditions across the value chain. Given the limited availability of comprehensive techno-economic studies of emerging biocomposites, this paper adds a qualitative perspective on the conditions that influence their adoption in industrial contexts. These insights inform a preliminary framework outlining the conditions under which biocomposites may progress toward competitive industrial performance. This study combines literature-based insights with preliminary insights from interviews across multiple stages of the biocomposite value chain to examine how organisations transition toward the use of biocomposite materials. Across the interviews, the emphasis is placed on meeting fundamental technical requirements, such as achieving process stability, consistent material quality, and alignment with established product specifications, as essential conditions for adoption. Interviewees also highlight that decisions increasingly draw on environmental performance data and highly economically driven scenario-based assessments. The reference material system is restricted to polyolefin matrices combined with cellulosic reinforcement or filler fractions, representing a baseline compound for which preliminary laboratory-level extrusion trials exist. Additives to improve weathering or fire performance are added at the early stages of the material base. Profile extrusion is selected as the industrially relevant processing method for continuous profiles across various construction applications. The technical system is represented as a conceptual process flow comprising feedstock preparation, compounding and pelletizing, pellet drying (as required), profile extrusion, and downstream calibration, cooling, haul-off, and cutting. These process blocks are described generically, and throughput values are estimated from various sources to reflect realistic economic drivers.

Keywords: Biocomposites, Economic Feasibility, Process Requirements, Industrial Adoption, Technology Assessment

1. Introduction

The increasing use of biocomposites offers the potential to replace fossil-based materials with more sustainable alternatives. These materials typically incorporate industrial fibre side streams, such as sawdust, agricultural residues, and pulp fibres, combined with polymers including polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC) through various manufacturing processes (Quarshie and Carruthers, 2014). Several application sectors, such as automotive components and decking wood plastic composites (WPC), have already successfully integrated biocomposites into large-scale production (Campilho, 2017). WPCs have gained extensive industrial acceptance by combining recycled plastics with wood-derived side streams, such as sawdust, and processing these materials into products like decking via extrusion. In 2019, Europe reported over 30 biocomposite producers, with an annual production volume exceeding 130,000 tons (Mason, 2026).

The market size is also very attractive to many players and new entrants, with a 2024 estimate of 33 billion dollars and rapid growth towards 111 billion by 2033, indicating strong promise for the adoption of biocomposites despite associated challenges (Sharma, 2025). These market developments are expected to attract manufacturers and material users seeking sustainable alternatives. In particular, biocomposites offer potential for applications requiring lightweight materials and reduced environmental impact.

Nevertheless, numerous challenges persist, including product specifications, compatibility issues, quality assurance, moisture-related problems affecting biocomposite properties, fabrication costs, supply chain availability, and inconsistent material sources, all of which necessitate advanced engineering systems (Andrew and Dhakal, 2022). Consequently, integrating biocomposites into existing manufacturing processes requires a thorough understanding of the materials before making investment decisions to optimise the benefits derived from these innovative material sources.

Although biocomposites have been already studied from material, processing, and sustainability perspectives, less attention has been given to how industrial actors evaluate the combined technical, process-related, and economic conditions required for adoption. Existing studies often examine individual barriers such as material performance, cost, or environmental impact separately, providing limited understanding of their interaction in industrial decision-making. This study addresses this gap by examining how industrial value-chain actors assess biocomposite adoption readiness and which techno-economic factors most strongly influence adoption decisions.

RQ1 What technical, process-level and techno-economic conditions shape the industrial adoption readiness of biocomposites in profile-extrusion-based applications?

RQ2 How do industrial value-chain actors evaluate the technical, process and economic conditions required for adopting emerging biocomposites in industrial applications?

By focusing on these questions, we aim to provide more information on novel material development, their potential, and the early lab-to-market possibilities, as well as the factors that affect the adoption of new technologies, using techno-economic decision criteria required for industrial adoption.

2. Methodology

This study combines evidence from a literature review, project documentation, market analyses, project meetings, and semi-structured interviews with industrial stakeholders. The objective is to develop a preliminary understanding of the technical, process-related, and techno-economic conditions influencing industrial biocomposite adoption. Given the exploratory nature of the study, the findings should be interpreted as indicative rather than statistically generalisable.

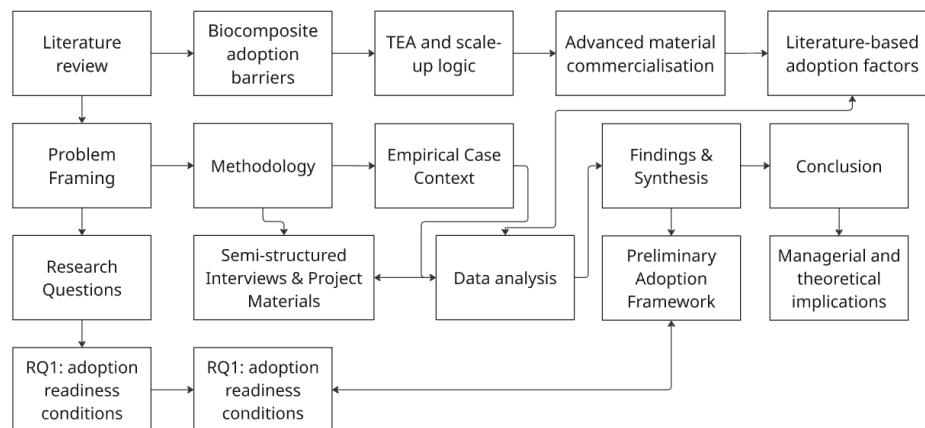


Figure 1: Overview of the preliminary research design and framework-building logic for assessing biocomposite adoption readiness

2.1 Literature Review Process for Papers

To ensure the rigour of the study's relevance (Arksey and O'Malley, 2005), various scoping search strategies were implemented to narrow down the most suitable research papers on biocomposites that were close to the project case study materials. Technical limitations are presented in case description chapter. Various programs were used to search for relevant literature, such as Litmaps, Google Scholar, Scopus, and Zotero for source control. The following topics and combinations were used to screen relevant papers: biocomposites, techno-economic analysis, life-cycle assessment, material-selection methods, circularity, and industrial scale-up. The purpose was to help synthesise supporting findings to understand material feasibility and scaling up from laboratory to industrial scale. The selected studies were used to identify transferable adoption factors. Each article was reviewed and summarized into different main categories; some papers were highly focused on certain aspects while some provided broader picture in this domain. From this preliminary study it is possible to continue towards further systematic review process. The process also involved project-related work to exchange information between other work packages to gain a better understanding of the domain-specific critical matters.

2.2 Interviews and Project Meetings

The primary empirical data for this study were collected through semi-structured interviews and project-related materials. Additional insights were obtained from project workshops involving material development experts, which helped define the problem setting and identify key areas for investigation. Respondents were selected through purposive sampling to represent different stages of the biocomposite value chain, including feedstock suppliers, material producers, manufacturers, and end users. In total, eight interviews were conducted, each lasting approximately one hour, with roughly half of the discussion dedicated to techno-economic assessment (TEA) topics. Semi-structured interviews were selected because they provide a consistent thematic structure while allowing respondents to elaborate on application-specific requirements, practical constraints, and adoption conditions (Kallio et al., 2016).

Interview transcripts were analysed using a Gioia-inspired thematic approach (Gioia, Corley and Hamilton, 2013). First-order concepts were identified directly from respondent statements and subsequently grouped into second-order themes related to technical requirements, process compatibility, economic feasibility, supply-chain readiness, and adoption conditions. The emerging themes were compared with findings from the literature review to identify converging and diverging factors affecting industrial biocomposite adoption. This approach provided a systematic structure for interpreting stakeholder perspectives and developing the preliminary adoption framework.

Table 1: Respondents background and connection to biocomposites domain

#	Value-Chain Role	Application Context
R1	Material / recycling actor	Polymer and composite materials
R2	Fibre or feedstock actor	Cellulosic raw materials
R3	Building product manufacturer	Profiles / construction components
R4	Biocomposite producer	Industrial compounds
R5	Industrial OEM / device manufacturer	Long-life components
R6	Marine / regulated end-user	Harsh environment applications
R7	Plastic product manufacturer	Moulded or processed components
R8	Circular material producer	Recycled and biobased products

The objective of the sample was not statistical representation but to capture diverse perspectives from key stakeholder groups involved in the development, production, adoption, and use of biocomposites. For the techno-economic part of the interview, the questions focused on the conditions under which biocomposites could become viable substitutes for existing materials in industrial applications. The design therefore addressed minimum technical performance requirements, acceptable cost levels, operational and investment-related barriers, manufacturing and quality assurance implications, supply-chain risks, and the techno-economic indicators most relevant for company decision-making. Benchmarking, scenario modelling and sensitivity analysis were also included to clarify what type of comparative evidence companies would need when assessing biocomposites against conventional material solutions.

3. Literature Review

3.1 Techno-Economic Analysis

In this study, techno-economic analysis (TEA) was originally planned for a preliminary level and mainly to identify core factors affecting the adoption of biocomposites in various parts of the value chain from production to end products and towards the end of life (EOL). Based on the literature review and general project feedback, TEA is an important step in adopting new concepts within business processes and should be treated as a core step in the planning stages. In recent years, the rise of digital simulation tools has increased, and predictions can become very detailed, including main economic and technical factors. (Chai *et al.*, 2022). In literature, biocomposites are complex items to estimate due to more factors compared to fossil-based plastics and much more variable material bases and related environmental push, which has many subsidised programs increasing estimation variables. It is typical also to include intricate carbon credit schemes (biochar stabilisation and burning side products), and there are trade-offs in properties between economic, technical and environmental

aspects. (Mousavi-Avval *et al.*, 2023) For this study, the adoption perspective and TEA are closely related, as often lab-scale testing fails to prove technology at industrial levels, and for that, TEA modelling is crucial to convince relevant actors of its feasibility (Zeng, 2025). Few studies about biocomposites in close fields (different material feeds) and TEA utilise life cycle costs (LCC), net present value (NPV) methods, sensitivity analysis to identify impactful economic factors, like investment into production facility, material costs, logistics, taxation, salaries, equipment and many others, depending on the situation. (Roy *et al.*, 2024)

3.2 New Technology Adoption in Material Domains

Biocomposites development can be viewed as a traditional adoption process with stage-gate decision-making and typical product design perspectives, aiming to view a holistic approach from the start when first material choices are made. In such a chain, process problems would be solved as they arise during implementation. The core focus is on customer needs and market pressure, combined with competitive advantages such as environmental pressures on fossil-based products. (Albiñana and Vila, 2012) This shows clearly that the first wave of biocomposites has been in relatively simple products like decking, with access to stable side streams. Another major step would be to diversify production towards more novel applications of biocomposites, which would require a deeper understanding of the material to produce higher-value products, an approach partially recognised in the study of advanced materials (Maine and Garnsey, 2006).

3.3 Biocomposites Adoption Barriers

Based on the literature, various issues and benefits have been presented over the last few decades of research. Still to this date, problems like moisture sensitivity, fibre matrix compatibility, thermal limits, flammability, supply variability, and processing challenges remain as challenges for advanced biomaterials adoption. (Andrew and Dhakal, 2022) As for the existing commercial product, WPC have already been recognised as an industrially mature and viable solution, though thermal issues like degradation are still present in 200 °C areas for wood-based side streams utilisation potential. A common way to improve weak properties is to use fillers to improve hydro stability or flame resistance and weather durability (UV), which is crucial in decking applications from an end product perspective. (Mitařová, Mitař and Berladir, 2024) The following table is a preliminary summary of various factors; the list is not exhaustive and is indicative for the study purpose.

Table 2: Summary of various identified adoption barriers according to various sources around biocomposites.

Adoption Factor	Relevant Contents	Source
Material variability	Natural fibres and wood-based fillers vary by source, particle size, moisture content, processing history and fibre treatment. This affects reproducibility and makes consistent product quality difficult.	(Faruk <i>et al.</i> , 2012)
Fiber–matrix compatibility	Cellulosic fillers are hydrophilic, while PP, PE and similar polyolefins are hydrophobic. This creates adhesion problems unless coupling agents or compatibilizers are used.	(dos Santos, Flores-Sahagun and Satyanarayana, 2015; Andrew and Dhakal, 2022)
Moisture resistance and durability	Moisture absorption, swelling, dimensional instability and weathering reduce adoption potential, especially in outdoor or construction-related products.	(Elsheikh <i>et al.</i> , 2022; Terzopoulou, Achilias and Vouvoudi, 2025)
Processing temperature limits	Cellulosic fillers have limited thermal stability, which restricts processing temperatures and narrows the process window for thermoplastics.	(Mitařová, Mitař and Berladir, 2024)
Filler loading trade-off	Increasing sawdust or fibre content improves renewable content and circularity, but can reduce tensile strength, increase water uptake, worsen melt flow and complicate extrusion.	(Hillig <i>et al.</i> , 2008; dos Santos, Flores-Sahagun and Satyanarayana, 2015; Friedrich, 2024)
Additives and compatibilizers	Coupling agents, lubricants, UV stabilisers, biocides, pigments and flame retardants are often needed to meet application requirements.	(Mitařová, Mitař and Berladir, 2024; Terzopoulou, Achilias and Vouvoudi, 2025)
Process compatibility	Biocomposites must fit existing extrusion, moulding or forming systems with limited disruption. Tooling, die design, feeding, cooling and calibration strongly affect feasibility.	(Hillig <i>et al.</i> , 2008; Friedrich, 2023)

Adoption Factor	Relevant Contents	Source
Product specification fit	Industrial users evaluate materials against application-specific requirements such as strength, dimensional stability, aesthetics, moisture resistance, fire behaviour and compliance.	(Andrew and Dhakal, 2022; Friedrich, 2023)
Supply-chain reliability	Feedstock collection, storage, preprocessing, drying, particle-size control and contamination management affect product quality and cost.	(Akbarian-Saravi <i>et al.</i> , 2025; Akbarian-Saravi, Sowlati and Milani, 2025)
Economic feasibility	Adoption depends on whether higher material or processing costs can be justified through performance, sustainability value, customer demand or regulatory advantage. Differences exists also in processing methods like extrusion vs. injection moulding.	(Immonen <i>et al.</i> , 2020; Friedrich, 2024)09/09/2026 15:31:00
Circular and regulatory value	Circular-economy incentives, recycling targets and environmental performance create adoption pressure, but they do not remove technical and economic requirements.	(Bledzki <i>et al.</i> , 2012; Fernández Fortunato, Jiménez-Sáez and Hontoria, 2023)

Although biocomposites have been widely studied, with more than 12,000 publications indexed in Scopus, direct techno-economic studies remain limited, particularly for sawdust-filled PE and PP matrix composites. Most prior research focuses on material performance, processing behaviour, environmental impacts, or individual adoption barriers in isolation. Comparatively less attention has been given to how industrial actors simultaneously evaluate technical, process, supply-chain, scalability, and economic considerations when making adoption decisions. Consequently, the interaction between these dimensions remains insufficiently understood from an integrated techno-economic perspective. This study addresses this gap by examining how industrial value-chain actors assess adoption readiness and how technical, process-related, and economic factors jointly shape industrial adoption decisions.

4. Case Description

The empirical context of this study is a research project focused on advanced biocomposites and circular design. The project develops and assesses biobased and recycled thermoplastic biocomposite solutions intended to replace fossil-based plastics and conventional composites in more demanding industrial applications. The project combines material and process development, circular design, end-of-life considerations, demonstration products, techno-economic assessment, regulatory analysis, and business model exploration. The case provides a relevant setting for examining how process requirements, industrial feasibility, sustainability expectations, and market-related factors shape the potential adoption of biocomposites in industrial value chains.

4.1 Technical Case Context: Material Formulation and Extrusion Processability

In the experimental part of this project, multiple different reference biocomposite materials were produced. The commercially available plastic matrices used were recycled polypropene and biobased low-density polyethylene. In addition, various additives and aids were used to improve processability, feeding behaviour and dispersion of the compounded materials. No additives were used to make chemical modifications. Sawdust and bleached softwood kraft pulp were used as fillers.

Plastic matrices and fillers were first dried overnight, then compounded and granulated for extrusion. All biocomposite materials were tested using a lab-scale single screw extruder. A typical extrusion trial set-up is depicted in Figure 2 below. As was expected, most of the biocomposite samples showed moderate or even poor surface quality during the first extrusion trials.



Figure 2: Left: Variation of the surface quality of biocomposite samples (Image: Reijo Heikkinen). Right: A lab-scale extruder producing a biocomposite profile. (Image: Kusti Ruokamo)

Process parameters were adjusted to improve feeding behaviour, melt flow and surface quality of the extruded biocomposite profiles. At higher filler contents, increased melt viscosity created clear processing challenges and limited stable material feeding. As the results are based on lab-scale trials, they should be interpreted as preliminary, but promising. Further process optimisation may improve manufacturability and support future scale-up potential in construction profiles and other suitable application areas for extrusion technology.

5. Findings

5.1 Interviews

The interview findings indicate that industrial adoption of biocomposites is not determined solely by material sustainability. Across respondents, adoption was mainly linked to biocomposites' ability to meet application-specific technical requirements, remain economically competitive, fit existing production systems, and provide a reliable supply at an industrial scale. The results, therefore, suggest that techno-economic feasibility depends on the combined assessment of material performance, processing compatibility, cost structure, investment needs, supply-chain readiness and evidence-based comparison with existing materials. As the empirical analysis is still preliminary, the interview material is summarised using a condensed Gioia-informed structure rather than a full coding model.

Table 3: Preliminary Gioia-style summary of interview-derived adoption conditions for biocomposites

First-Order Interview Signals, Condensed	Second-Order Theme	Aggregate Dimension
Must match plastics, aluminium, steel or current composites in the target use case.	Technical equivalence	Application-specific performance threshold
Outdoor, marine and long-life uses require durability, weather resistance, fire behaviour, fixing and aesthetics.	Application-specific technical fit	Application-specific performance threshold
Material must be stable, consistent, processable and compatible with dies, moulds and temperature windows.	Process stability and manufacturability	Process compatibility
Material change may require tooling, mould modifications, QA changes, new lines or capital investment.	Operational adaptation requirements	Process compatibility
€/kg and €/part must be close to incumbent materials unless a clear value premium is justified.	Cost parity or value justification	Economic feasibility
Decisions depend on production volume, payback time, process route and raw-material price sensitivity.	Investment and payback logic	Economic feasibility
Industrial users require stable supply, predictable quality, traceability and documentation.	Supply-chain reliability	Scale and supply readiness
Confirmed customer demand, partner capability and sufficient application volume are needed before scale-up.	Market pull and ecosystem readiness	Scale and supply readiness
CO ₂ footprint, LCA, circularity, recycling and regulation increasingly support material evaluation.	Environmental and regulatory value	External adoption drivers
Benchmarking and scenario modelling are needed against current material references and regulatory shifts.	Comparative evidence and scenario TEA	Decision-support logic

The preliminary interview results indicate that biocomposite adoption is mainly shaped by interrelated conditions: technical equivalence, application-specific fit, process compatibility, economic feasibility, supply-chain reliability, and evidence-based comparison with existing materials. Based on the interview findings, the aggregate dimensions can be interpreted as preliminary adoption-readiness propositions requiring validation in future studies.

5.2 Data Analysis and Comparison with Literature-Derived Adoption Factors

First, respondents emphasised that biocomposites must meet the minimum technical requirements of the target application before sustainability benefits become commercially relevant. These requirements vary strongly by use case, with stricter expectations in outdoor, long-life, marine, construction, and regulated environments. While previous studies have identified performance requirements as adoption barriers, the interviews suggest that industrial actors evaluate these requirements primarily through application-specific risk. This indicates that adoption decisions are not driven solely by material properties, but by the consequences of failure within the intended application context.

Second, process compatibility was repeatedly identified as a practical adoption condition. Biocomposites need to fit existing production systems, tooling, quality assurance routines, and subcontractor processes with limited disruption. Where major process changes or new investments are required, adoption risk increases. The findings suggest that process compatibility may represent a stronger adoption constraint than material performance itself. Even technically promising materials may face resistance if implementation requires substantial modifications to existing production systems, tooling, or quality-control procedures.

Third, cost competitiveness remains central. Respondents indicated that biocomposites should remain close to the cost level of incumbent materials, unless they provide a clearly demonstrable value premium through lower carbon footprint, circularity, weight reduction, regulatory advantage, or stronger sustainability positioning. The interviews indicate that cost competitiveness is evaluated relative to perceived value rather than solely on material price. This suggests that successful adoption may depend on demonstrating measurable operational, regulatory, or sustainability benefits that justify a cost premium.

Fourth, stable supply and material consistency were seen as decisive for industrial use. Respondents highlighted that predictable quality, sufficient volumes, documentation, traceability, and supplier reliability are necessary before biocomposites can move from trial use to wider adoption. This finding indicates that supply-chain readiness may become a decisive adoption factor once the minimum technical requirements are met. Respondents also highlighted that feedstock variability, evolving recycling streams, and inconsistent material compositions may challenge stable product quality at an industrial scale. These concerns extend beyond material properties to include logistics, traceability, recycling infrastructure, and evolving producer responsibility requirements. Furthermore, degradation effects and material-property fluctuations may limit the reuse of recycled biocomposite streams, creating additional challenges for maintaining consistent performance and supply reliability.

Finally, the interviews suggest that companies need comparative evidence before committing to new materials. Benchmarking against existing materials, scenario-based techno-economic assessment, and sensitivity analysis were considered useful tools for evaluating costs, performance, lifecycle value, investment risk, and demand uncertainty. This was partially related to literature reviews, which mostly tested different stocks and possibilities. The challenge is to demonstrate industrial adoption scale convincingly; respondents would require more than small-scale lab tests to adopt biocomposites at scale. Overall, the interview results suggest that biocomposite adoption requires moving from general sustainability promises toward application-specific techno-economic evidence. Rather than evaluating technical, economic, or sustainability factors independently, respondents viewed adoption as a combination of interconnected conditions. Material performance, processing feasibility, cost structure, supply readiness, and comparative value, therefore, need to be assessed together at the system level before industrial-scale-up decisions can be justified.

5.3 Answers to Research Questions

RQ1 Technical readiness depends on meeting application-specific requirements such as durability, moisture resistance, dimensional stability, fire retardancy, mechanical performance, aesthetics and compliance. In profile extrusion, process readiness is also critical, as feeding behaviour, melt flow, surface quality, die compatibility, and calibration affect manufacturability. Techno-economic readiness extends beyond material price and should include €/kg, €/part, production volume, throughput, tooling and QA needs, investment costs, payback time, supply risks and raw material price sensitivity. Overall, adoption depends on whether biocomposites can move from laboratory promise to stable, repeatable and economically justified production.

RQ2 Interviewed actors evaluated biocomposites mainly by comparing them with incumbent materials such as plastics, aluminium, steel and existing composites. Their evaluation logic was practical and risk-oriented, focusing on performance, production disruption, cost level, supplier reliability, documentation, regulatory relevance and customer acceptance. Sustainability value was seen as beneficial, but only after basic technical and economic requirements are met. Therefore, companies require benchmarking, scenario modelling and sensitivity analysis before committing to larger trials or investment.

6. Conclusion

Biocomposites adoption does not rely on a single strong factor but on a combination of various requirements, as described in the literature and interviews, evident in lab-scale tests and in benchmarking against existing companies (Trex, 2025) with seemingly similar products and collection lines to produce biocomposites. This paper connects industrial value-chain perspectives with material and processing barriers through a qualitative perspective. While the existing literature typically examines material performance, environmental impacts, or economic feasibility separately, the findings suggest that industrial adoption decisions are based on the interaction among technical equivalence, process compatibility, economic feasibility, supply readiness, and comparative evidence. These insights can guide future TEA modelling of sustainable biocomposite development and adoption.

The study contributes a preliminary adoption-readiness framework that extends prior adoption-barrier studies by integrating technical, process, supply-chain, and economic factors into a single adoption-readiness perspective. In practice, the framework can support early-stage screening of novel, untested biocomposite opportunities by helping developers identify critical requirements before major scale-up decisions. The key adoption conditions identified in this study are:

- Technical equivalence
- Application-specific fit
- Process compatibility
- Economic feasibility
- Scale and supply readiness
- Comparative evidence

On a lab scale, various trials should be conducted to verify quality and adjust parameters. From an economic perspective, companies can compare core factors such as €/kg and total process adoption costs for adoption review. For suppliers, biocomposites need to be well-defined, and traceability is crucial to maintain a consistent supply or accommodate changes in process parameters. There are already indications of upcoming regulations for material characterisation supporting directions, and many companies are strongly committed to environmental product declarations (EPDs) combined with LCA. (Olanrewaju, Enegbuma and Donn, 2025)

6.1 Limitations and Future Research Directions

The purpose of the study was not to provide a complete TEA model, but to identify the adoption conditions that should guide future techno-economic modelling for biocomposites in more demanding application areas.

Due to the exploratory nature of the study and the limited number of interviews, the findings should be considered indicative and validated through larger cross-sector studies.

Ethics Declaration

This study is based on semi-structured interviews with professionals representing different stages of the biocomposite value chain. Participation was voluntary, and the study's purpose was explained to the respondents. The interview data were anonymised, and no personal or sensitive data were reported in the paper.

AI Declaration

Artificial intelligence tools were used only for language refinement, including sentence condensation, grammar correction, and readability improvement. AI was not used to interpret interview data, conduct the analysis, or generate the conclusions. All analytical decisions and final interpretations remain the responsibility of the authors.

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