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Article

Integrating Bioeconomy Principles in Bionic Production: Enhancing Sustainability and Environmental Performance

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Abstract: The integration of bioeconomy principles in bionic production holds promise for enhancing sustainability and resource efficiency. This scientific article aims to investigate the potential of bioeconomy-driven approaches in bionic production, focusing on the utilization of renewable biological resources, sustainable manufacturing techniques, and circular design strategies. The research questions guide the exploration of resource utilization, manufacturing techniques, waste reduction, environmental impact assessment, and economic considerations. The article presents a conceptual framework that integrates bioeconomy principles throughout the life cycle of bionic products, validating the proposed concepts and methodologies. By embracing bioeconomy principles, this article highlights the potential of bionic production to contribute to sustainable development, resource conservation, and the transition toward a bioeconomy.

Keywords: bioeconomy; bionic production; sustainability; renewable biological resources; bio-based materials; sustainable manufacturing; environmental performance

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1. Introduction

There has been a growing interest in exploring the application of bioeconomy principles in bionic production and their potential contributions to environmental protection, sustainable production, and resource efficiency (Alves Filho et al. 2018; Ding-yi et al. 2019; García-Domínguez et al. 2020; Kiyokawa et al. 2022; Liu et al. 2018; Morales and Lhuillery 2021; Nielsen et al. 2023; Okada et al. 2022; Yang et al. 2021). Industries across diverse sectors aim to incorporate bio-inspired designs and renewable biological resources into their production processes.

While existing literature has examined aspects of bioeconomy integration in various industries, there is a clear need for a more focused and comprehensive examination tailored to bionic production. Existing practices often adopt bioeconomy standards and methodologies without the critical analysis required to fully exploit their potential (Walzberg et al. 2021).

Traditional biotech practices have often prioritised short-term economic gains over long-term environmental impacts. This highlights the need for a comprehensive examination of Green Robotics concepts and strategies (Alves Filho et al. 2018), additive manufacturing's role in sustainable development (Ding-yi et al. 2019), standardisation developments in additive manufacturing (García-Domínguez et al. 2020), waste sorting automation through robots (Kiyokawa et al. 2022), realising the benefits of robotic process automation in supply chains (Nielsen et al. 2023), and Six-Sigma quality management of additive manufacturing (Yang et al. 2021).

One of the key focuses within the realm of bioeconomy-driven bionic production has been the utilisation of renewable biological resources. Researchers and practitioners have increasingly turned to sustainable and eco-friendly sources for bio-based materials (Colorado et al. 2020). These materials, ranging from biopolymers to biomimetic substances, offer the potential to reduce reliance on non-renewable resources, particularly fossil fuels.

Furthermore, the integration of bioeconomy principles has spurred the adoption of sustainable design and manufacturing practices (Cherepanov et al. 2021; Schumacher et al. 2020). Drawing inspiration from nature, these approaches seek to optimise production processes, minimise waste generation, and enhance resource efficiency. This not only aligns with sustainability goals but also opens doors to innovative bio-inspired designs in bionic production.

A holistic perspective, encompassing the entire life cycle of bionic products, has become paramount (Moosavi et al. 2021). Life cycle assessments (LCAs) have been instrumental in evaluating the environmental impacts associated with bioeconomy-integrated bionic production. Factors such as energy consumption, greenhouse gas emissions, and water usage have been scrutinised to ensure a comprehensive understanding of sustainability implications.

Circular design strategies, a core tenet of bioeconomy principles, have gained prominence. These strategies aim to create closed-loop systems, reducing the need for virgin materials and minimising waste generation. Modular designs and products designed for easy disassembly have emerged as strategies to enable efficient repair, remanufacturing, or recycling (Mishra et al. 2021).

Collaboration among stakeholders, including researchers, manufacturers, policymakers, and consumers, has been recognised as a linchpin in advancing bioeconomy-driven approaches in bionic production (Deloitte 2023; Kreuzer et al. 2018). By fostering knowledge exchange, interdisciplinary cooperation, and dialogue, stakeholders have collectively driven innovation and addressed challenges in resource-efficient manufacturing.

Economic feasibility and market potential have emerged as crucial considerations. Researchers and industry players have undertaken assessments to determine the cost-effectiveness of bio-based materials, the scalability of sustainable manufacturing techniques, and the market viability of bioeconomy-driven products (Mishra et al. 2021). The economic aspect plays a pivotal role in steering the adoption and commercialisation of these principles.

While significant progress has been made in these areas, it is essential to acknowledge that the field of bioeconomy-integrated bionic production is continually evolving. Recent findings and emerging technologies have the potential to reshape practices and unlock new avenues for sustainability and innovation.

The novelty of this research lies in its comprehensive examination of the integration of bioeconomy principles into bionic production processes, addressing the latest advancements and challenges. This study bridges the gap between various domains, encompassing Green Robotics, additive manufacturing, standardisation, waste sorting automation, benefits realisation in supply chains, and quality management of additive manufacturing. By synthesising these diverse areas, the research provides a holistic perspective on how bioeconomy principles can be integrated into bionic production.

The primary goal of this research is to explore the integration of bioeconomy principles in bionic production processes and assess their impact on sustainability and environmental performance. To achieve this goal, a comprehensive literature review was employed, relevant case studies were analysed, and the design science research method was applied.

Through critical analysis and interpretation of existing research and real-world case studies, this research aims to guide the design and development of innovative strategies and frameworks for enhancing sustainability in bionic production. The research questions driving this study are:

- What is the potential of renewable biological resources for bionic production, and how can their availability, properties, and suitability be assessed?
- How can sustainable manufacturing techniques and processes be identified and evaluated to align with bioeconomy principles in bionic production?
- What strategies and methodologies can be developed to optimise resource efficiency and minimise waste generation in bionic production, fostering a bioeconomy approach?

- How can life cycle assessments (LCA) be conducted to assess the environmental impact and sustainability performance of bioeconomy-integrated bionic production processes?
- What is the economic feasibility and market potential of bioeconomy-driven bionic production, considering the cost-effectiveness of bio-based materials and the scalability of sustainable manufacturing techniques?

The paper is structured in a logical progression, encompassing several key sections. The materials and methods section outlines the research approach and methodologies employed in the study, including the selection criteria and analysis of relevant literature, as well as the measurements and data utilised. The results section comprehensively presents the research findings, encompassing relevant quantitative and qualitative data, measurements, and insightful information. It provides an in-depth examination of existing research works related to the integration of bioeconomy principles in bionic production. It explores concepts such as renewable biological resources, bio-based materials, sustainable manufacturing techniques, and bioeconomy approaches.

Through critical analysis and interpretation, the discussion section provides valuable insight into the significance of the research findings. It explores the challenges and opportunities associated with the integration of bioeconomy principles in bionic production and highlights the potential for achieving sustainable outcomes. Furthermore, the discussion section examines the practical implications of this integration and provides recommendations for industry stakeholders, policymakers, and researchers.

2. Materials and Methods

This study employs a combination of the Design Science research method and a thorough literature review to fulfil its objectives.

2.1. Literature Review and Selection Criteria

A comprehensive examination of the literature was carried out by searching key databases such as PubMed, IEEE Xplore, ScienceDirect, Scopus, and Google Scholar. Search terms included “bioeconomy”, “bionic production”, “renewable biological resources”, “sustainable manufacturing”, and “environmental impact assessment”, among others.

To ensure data quality and relevance, selection criteria were applied. Only peer-reviewed scientific articles and reputable reports published in the last five years (with some exceptions) were considered. Additionally, articles had to align with the research focus and provide relevant data and measurements.

2.2. Data Collection

A total of 61 publications between 2018 and 2023 were examined, including research articles, review articles, conference papers, books, and reports. Data collection involved extracting pertinent information related to renewable biological resources, bio-based materials, sustainable manufacturing techniques, environmental impact assessments, life cycle assessments (LCA), and economic feasibility studies.

2.3. Conceptual Framework

Based on the outcomes derived from the literature and data analyses, a conceptual framework was developed to guide the incorporation of bioeconomy principles throughout the bionic product life cycle. The methodology employed in this research paper is based on the research strategy known as Design Science, as proposed by Holmström et al. (2009). Design Science is a research approach that focuses on the creation and evaluation of innovative artefacts to address practical problems or improve existing practices.

Table 1 offers a succinct summary of the practical conceptual framework for integrating bioeconomy principles into bionic production. It delineates the stages of problem identification, the core components of the framework (including renewable biological resources, sustainable manufacturing techniques, resource efficiency, waste reduction, and life cycle assessments), and the connections among these components.

Table 1. Practical conceptual framework for integrating bioeconomy principles in bionic production.

Stage	Description
1. Problem Identification	– Identify challenges and opportunities associated with integrating bioeconomy principles into bionic production. – Assess the impact of current practices on sustainability and environmental performance.
2. Key Elements of the Framework:	
Renewable Biological Resources	– Promote the use of renewable and biodegradable resources in bionic production. – Encourage sustainable sourcing and cultivation of biological materials.
Sustainable Manufacturing Techniques	– Implement eco-friendly and energy-efficient manufacturing processes. – Reduce the use of harmful chemicals and pollutants. – Adopt technologies aimed at waste and emissions reduction.
Resource Efficiency	– Optimise resource utilisation through efficient production methods. – Implement strategies to reduce material waste and promote recycling.
Waste Reduction	– Adopt strategies for waste prevention and reduction throughout the product life cycle. – Implement circular economy principles to minimise waste generation.
Life Cycle Assessments	– Conduct comprehensive life cycle assessments to evaluate the environmental impact of bionic products. – Consider the complete life cycle, including raw material extraction, production, use, and disposal.
3. Interrelationships	– The framework recognises the interdependencies among the key elements. – Renewable biological resources contribute to sustainable manufacturing techniques and resource efficiency. – Sustainable manufacturing techniques and resource efficiency contribute to waste reduction. – Life cycle assessments inform decision-making and guide improvements across all elements.

The conceptual framework provides a structured approach to integrating bioeconomy principles into bionic production. It serves as a guide for decision-making, strategy development, and the implementation of sustainable practices.

2.4. Analysis and Interpretation

The gathered data and information were analysed and interpreted to derive meaningful insights and draw conclusions. This involved comparing and contrasting the findings from different sources, identifying patterns or trends, and assessing the strengths and limitations of the measurements in the existing studies (Gardiner 2016; Boston Consulting Group 2020). The analysis encompassed a comprehensive examination of both qualitative and quantitative aspects, tailored to the specific characteristics and availability of the data.

2.5. Selection of Real-World Case Studies

To validate and exemplify the proposed concepts and methodologies, real-world case studies were analysed. These case studies serve as practical examples of the integration of bioeconomy principles in bionic production, showcasing their potential to achieve sustainable and environmentally conscious outcomes. The selection of these case studies was based on their alignment with research questions and the availability of reliable data and measurements (Gardiner 2016; Boston Consulting Group 2020). The chosen case studies encompassed a diverse range of applications within bionic production. Specifically, they included an exploration of 3D printing techniques, the utilisation of short-rotation coppice (SRC) for dendromass production, and an examination of waste biorefineries as practical instances demonstrating the incorporation of bioeconomy principles in different dimensions of bionic production. The case study exploring the social aspects of SRC-based dendromass production in Eastern Slovakia (Fürtner et al. 2021) facilitated the extraction of pertinent insights into the intricate nexus of renewable biological resources, sustainable manufacturing techniques, and the socioeconomic dimensions of bioeconomy-driven production.

Likewise, the case study on waste biorefinery conducted by Leong et al. (2021) provided a thorough examination of the mechanisms behind waste valorisation. It meticulously examined the feasibility of waste biorefineries and critically appraised the challenges associated with waste collection, segregation, and processing.

In the domain of 3D bioprinting, as delineated in the case study authored by Tyrer-Jones (2023), the research undertook a systematic exploration of the convergence of renewable biological resources, sustainable manufacturing techniques, and circular design strategies. The analysis extended to a rigorous assessment of the safety and efficacy of bioprinted constructs, ensuring that innovation remains rooted in practicality.

3. Results

The research efforts have yielded significant insights into the integration of bioeconomy principles in bionic production. Critical findings underscore the potential of bio-based materials, sustainable manufacturing techniques, and bio-inspired design strategies to foster sustainability and environmental consciousness within bionic production.

3.1. Integration of Bioeconomy Principles in Bionic Production

The analysis of the selected articles revealed several prominent themes that surfaced throughout the investigation. Firstly, the utilisation of renewable biological sources, like bio-based materials and biomass, was identified as a crucial aspect of bioeconomy-integrated bionic production. Various studies have demonstrated the potential of bio-based materials to achieve sustainable and environmentally friendly outcomes in bionic production processes. The properties, availability, and suitability of these renewable resources were assessed, providing insights into material selection and resource utilisation strategies.

Bioeconomy principles have received increasing attention for their role in improving bionic production. Bionic production draws inspiration from natural systems to create innovative products with enhanced functionality and efficiency. By imitating biological structures and processes, bionic production aims to develop designs and manufacturing techniques that optimise resource utilisation and minimise environmental impact.

The integration of bioeconomy principles into bionic production presents a multitude of potential advantages:

- Utilisation of Renewable Biological Resources: This facet encompasses the incorporation of bio-based materials sourced from renewable feedstocks, such as plant-based polymers, biomaterials, and biocomposites. This strategic shift from fossil fuel-based materials to bio-based alternatives plays a pivotal role in diminishing reliance on finite resources and ameliorating environmental impacts (Rosenboom et al. 2022; Roumeli et al. 2022; Malla et al. 2023). The findings emphasise the importance of incorporating renewable biological resources and provide insights into their properties, availability, and suitability, facilitating their assessment.
- Bio-Inspired Design: Inspired by the intricacies of biological structures and functions, bionic designers have endeavoured to fashion products that possess augmented performance and efficiency. These biomimetic designs often entail meticulous optimisation of material usage, weight reduction, and performance enhancement, all of which culminate in the creation of more sustainable and resource-efficient products (Bélanger-Barrette 2021; Feliu-Talegon et al. 2020; Price et al. 2022).
- Sustainable Manufacturing Techniques: These methodologies prioritise resource efficiency, waste reduction, and energy optimisation. Noteworthy examples encompass additive manufacturing and biofabrication, which enable precision and customisation

in production, consequently curtailing material waste and energy consumption (Javaid et al. 2022; Siciliano and Khatib 2016; Scown and Keasling 2022).

- Bioeconomy Approach: Extending beyond the confines of the production phase, the bioeconomy approach encompasses the entire lifecycle of a product, including its use, maintenance, and end-of-life phases. Implementation of strategies such as recycling, reusing, and remanufacturing serves to minimise waste generation and prolong product lifespans, thereby curbing environmental impact (Dahiya et al. 2022; Sinha and Modak 2021; Davis-Peccoud et al. 2021).
- Environmental Protection: Bionic production, grounded in the utilisation of renewable biological resources and the optimisation of material usage and energy consumption, emerges as a significant contributor to environmental protection. Its potential to mitigate greenhouse gas emissions, diminish pollution, and preserve ecosystems holds promise (Tõnnisson and Schmerber 2018; Zheng and Suh 2019).

To successfully integrate bioeconomy principles in bionic production, various aspects need to be considered, including material selection, manufacturing processes, design optimisation, and product life cycle assessment. Collaboration between researchers, industry stakeholders, and policymakers is crucial to drive innovation, develop sustainable practices, and overcome challenges associated with the implementation of bioeconomy principles in bionic production.

3.2. Sustainable Manufacturing Techniques and Processes

The analysis of the selected literature has underscored the paramount significance of sustainable manufacturing techniques and processes within the context of bionic production. Two particularly promising approaches that emerged from this review are additive manufacturing and biofabrication, both of which exhibit substantial potential for resource-efficient production and waste reduction. These techniques facilitate precise and customised manufacturing processes, ultimately leading to minimised material waste and reduced energy consumption. Several instances of bionic products manufactured using these methods have demonstrated their capacity to yield sustainable outcomes.

The effective incorporation of bioeconomy principles into bionic production hinges on the adoption of sustainable manufacturing techniques and processes. These methodologies are designed to optimise resource utilisation, diminish waste generation, and curtail environmental impact across the entire manufacturing lifecycle. By embracing sustainable manufacturing practices, bionic production stands to achieve heightened levels of sustainability, efficiency, and environmental performance (Li et al. 2020).

Key sustainable manufacturing techniques and processes that align with the integration of bioeconomy principles in bionic production include:

- Additive Manufacturing significantly reduces material consumption by building products layer by layer. It enables precise customisation, rapid prototyping, and lightweight design, leading to resource-efficient manufacturing (Abdulhameed et al. 2019; Bournias Varotsis 2021; Javaid et al. 2022; Kokare et al. 2023; Li and Yeo 2021).
- Biofabrication creates functional tissues and structures using living cells and biomaterials, melding biology, engineering, and materials science. Methods like bioprinting and tissue engineering reduce material waste and reliance on animal testing, embracing renewable biological resources (Jones et al. 2021; Schiros et al. 2021).
- Lean Manufacturing minimises waste, enhances efficiency, and boosts productivity by eliminating unnecessary production activities. Lean manufacturing optimises workflows, reduces waste, and streamlines processes to enhance resource efficiency and environmental sustainability (Jadhav and Ekbote 2021).
- Closed-Loop Manufacturing (also known as Circular Manufacturing): This approach designs products and processes to generate minimal waste, favouring effective material recovery and reuse. It aligns with bioeconomy principles and fosters sustainable resource management (Häußler et al. 2021).

- Energy Efficiency (also known as Circular Manufacturing): this approach designs products and processes to generate minimal waste, favouring effective material recovery and reuse. It aligns with bioeconomy principles and fosters sustainable resource management (Häußler et al. 2021).
- Supply Chain Optimisation: Extending beyond single facilities, sustainable manufacturing considers the entire supply chain. Optimising it entails reducing transportation distances, selecting eco-friendly suppliers, and ensuring transparency and ethics, thus minimising emissions, promoting responsible sourcing, and supporting sustainability (Gopalakrishnan 2022).

Figure 1 illustrates a systematic approach to identifying and evaluating key sustainable manufacturing techniques. It highlights key steps involved in the process, starting with the identification of relevant techniques and moving through evaluation and selection. The figure emphasises the importance of considering sustainability criteria and performance indicators during the evaluation process. Overall, the figure provides a visual representation of the systematic approach used to identify and assess sustainable manufacturing techniques in order to promote more environmentally friendly and socially responsible manufacturing practices.

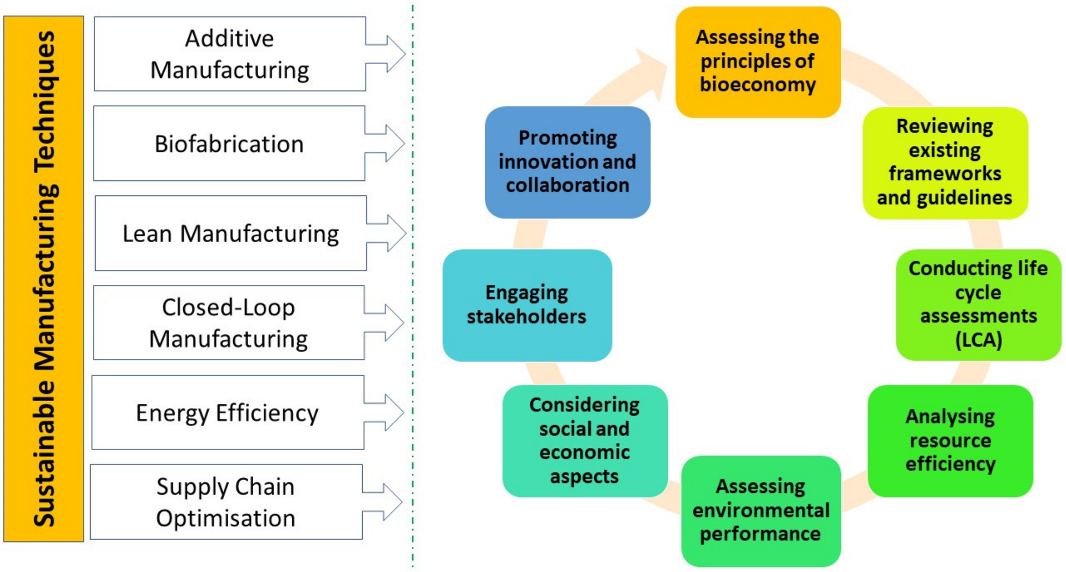

Figure 1. A systematic approach for identifying and evaluating key sustainable manufacturing techniques. Source: authors.

Identifying and evaluating sustainable manufacturing techniques and processes that align with bioeconomy principles in bionic production requires a systematic approach and consideration of key factors. Some steps to consider include:

- Understanding bioeconomy principles: Assess the bioeconomy's core principles, including renewable resource use, waste valorisation, and resource efficiency. These principles guide the identification of sustainable manufacturing techniques.
- Utilising established frameworks: Review existing sustainability-related frameworks and standards like ISO 14001 (Environmental Management Systems) and ISO 50001 (Energy Management Systems). They serve as bases for evaluating manufacturing techniques' sustainability (Sartor et al. 2019; Prasetya et al. 2021).
- Conducting life cycle assessments (LCA): Conducting LCA is a valuable approach to evaluating the environmental implications of different manufacturing techniques and processes throughout their life cycles. LCA provides insights into areas of concern and opportunities for improvement, considering factors such as energy consumption, greenhouse gas emissions, water usage, and waste generation.

- Analysing resource efficiency: Evaluate material usage, energy efficiency, waste reduction, and circularity aspects. Seek techniques that minimise resource consumption and promote closed-loop systems.
- Assessing environmental performance: Consider environmental performance indicators like carbon, water, and ecological footprints. Compare different techniques to identify those with lower environmental impacts.
- Evaluating social and economic aspects: Beyond environmental factors, assess social and economic aspects, such as job creation, worker safety, and local economic development.
- Engaging stakeholders: Involve manufacturers, researchers, policymakers, and consumers in evaluations. Seek their input and expertise for a comprehensive assessment.
- Promoting innovation and collaboration: Encourage innovation in bionic production by fostering collaborative efforts between academia, industry, and government agencies. Support research and development efforts to explore new sustainable manufacturing techniques and processes that align with bioeconomy principles (Gasparetto and Scalera 2019).

Furthermore, integrating digital technologies, data analytics, and life cycle assessment tools can offer insights into the environmental impact of various manufacturing approaches and facilitate decision-making towards more sustainable practices.

3.3. Life Cycle Assessment (LCA) of Bioeconomy-Integrated Bionic Production

The utilisation of life cycle assessment (LCA) in the domain of bioeconomy-integrated bionic production presents both opportunities and challenges, calling for a rigorous and critical examination of its application. While LCA is a well-established tool for evaluating environmental impacts, its implementation in this specialised context necessitates a more profound and discerning evaluation.

LCA serves as a fundamental means to assess the complete life cycle of products, encompassing raw material extraction, production, use, and disposal phases. In the domain of bioeconomy-integrated bionic production, it offers valuable insights into the environmental implications of incorporating renewable biological resources and sustainable manufacturing techniques (Hosseinzadeh-Bandbafha et al. 2021; Fürtner et al. 2021). Such insights can guide decision-making towards more eco-friendly and efficient practices.

Nevertheless, the unquestioning adoption and application of standardised LCA methodologies may pose limitations and hinder the depth of analysis required for this intricate subject. One critical area is the definition of the system boundary, where delineating the extent of the life cycle stages to include or exclude becomes crucial. The selection of specific stages profoundly impacts the overall results and interpretations. Consequently, a thorough understanding of the interrelationships between different stages and their potential ripple effects is essential.

The availability and accuracy of data emerge as another focal point for critical scrutiny in bioeconomy-integrated bionic production LCAs. Obtaining comprehensive and reliable data on the environmental impacts of bio-based materials, renewable resources, and various manufacturing processes can be challenging. Variations in data sources and quality may introduce uncertainties, demanding methodological adaptability and careful interpretation (Heidari et al. 2019).

Moreover, the choice of impact categories and characterisation models in LCA warrants a closer examination. While conventional impact categories like greenhouse gas emissions, energy consumption, and water usage are commonly assessed, they may not adequately address the unique sustainability aspects of bioeconomy-integrated bionic production. To enhance the relevance and accuracy of LCA, customised impact categories should be developed, aligning with the specific objectives and contextual realities.

The issue of allocation in LCA studies, particularly when co-products and by-products are involved, demands careful deliberation. Different allocation methods can yield diverse environmental performance results, raising the need for transparent justifications and unbiased reporting (Wymenga et al. 2013).

Furthermore, the interpretation and reporting of LCA findings require a nuanced approach. Transparently addressing uncertainties, assumptions, and limitations is paramount to avoiding potential misinterpretations and misguided conclusions. A comprehensive analysis should acknowledge the trade-offs between different environmental, social, and economic dimensions to foster a holistic understanding of sustainability (Zeug et al. 2021).

To elevate the critical analysis of LCA in bioeconomy-integrated bionic production, researchers must actively engage in overcoming these challenges. Developing robust methodologies that suit the intricacies of bio-based materials, sustainable manufacturing techniques, and the entire product life cycle is crucial. Collaborative efforts involving experts from diverse fields and stakeholders can contribute to filling data gaps and enhancing the reliability of LCA outcomes (Tišma and Mileusnić Škrtić 2023).

Incorporating broader sustainability considerations, including social and economic dimensions, is indispensable to promoting a more comprehensive evaluation of bioeconomy-integrated bionic production's impact. Additionally, the inclusion of different stakeholder perspectives facilitates a more inclusive and informed LCA process.

In conclusion, LCA remains a valuable tool for assessing the environmental sustainability of bioeconomy-integrated bionic production. However, a critical analysis of its standards, methodologies, and contextual relevance is vital to maximising its potential and fostering well-informed decision-making in the pursuit of a resilient and balanced bioeconomy. By addressing the challenges through a discerning lens, researchers can strengthen the credibility and applicability of LCA and contribute to the sustainable transformation of bionic production practices.

Figure 2 illustrates a systematic approach to integrating bioeconomy principles into bionic production while considering key LCA considerations and implementing sustainable manufacturing techniques.

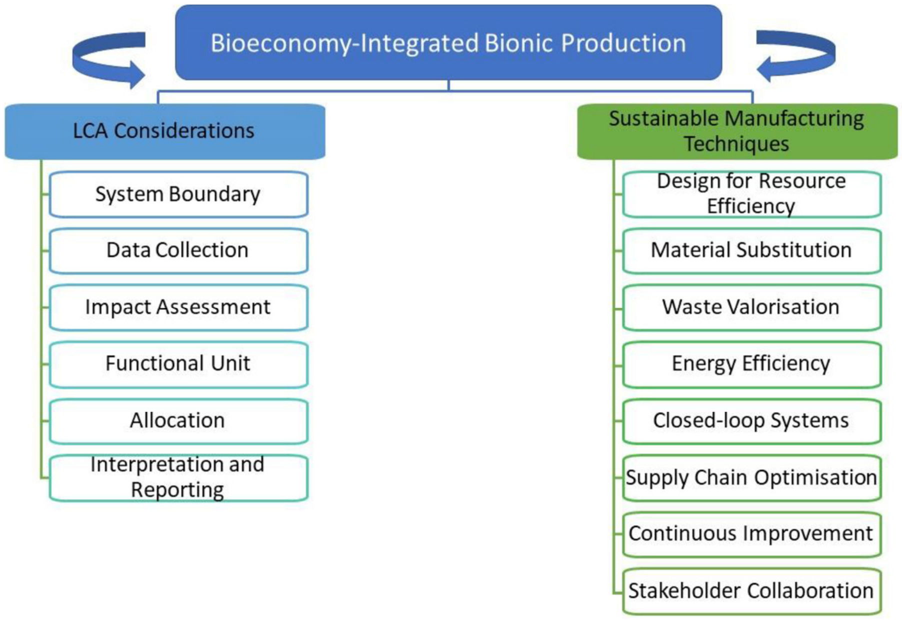

Figure 2. Integrated approach to sustainable manufacturing in bioeconomy-integrated bionic production. Source: authors.

To optimise resource efficiency and minimise waste generation in bionic production, several strategies and methodologies can be developed. These approaches aim to align with the principles of the bioeconomy, which emphasise the efficient use of resources, waste valorisation, and circularity. The strategies and methodologies that can be implemented, though not limited to, are:

- Design for Resource Efficiency: Prioritise resource-efficient design from the product's inception. This includes selecting renewable, recyclable, or biodegradable materials and incorporating modular and standardised interfaces for easy disassembly and recycling.
- Material Substitution: Replace harmful materials with sustainable alternatives. Bio-based materials like plant-based polymers and natural fibres offer eco-friendly options. Use life cycle assessments (LCAs) to assess environmental impacts and resource efficiency in material choices.
- Waste Valorisation: Maximise waste utilisation by recycling, upcycling, or repurposing it for new products or manufacturing processes. Recognise waste as a valuable resource to create a circular, sustainable production system.
- Energy Efficiency: Boost energy efficiency with energy-saving technologies, process optimisation, and renewable energy use. These measures cut energy consumption and enhance resource-efficient production.
- Closed-loop Systems: Develop closed-loop systems to minimise material and resource losses. Strategies include waste reduction, recycling, and reusing materials to establish a continuous resource flow and reduce waste.
- Supply Chain Optimisation: Optimise the supply chain by reducing resource consumption and waste. Efficient logistics, shorter transportation distances, and sustainable supplier choices, supported by stakeholder collaboration, ensure transparency and traceability.
- Continuous Improvement: Foster a culture of continuous improvement by implementing lean manufacturing principles and regularly evaluating and optimising processes. Engaging employees in identifying resource efficiency improvements and waste reduction opportunities contributes to ongoing progress.
- Stakeholder Collaboration: Collaborate with stakeholders, including manufacturers, researchers, policymakers, and consumers, to promote a bioeconomy approach in bionic production. Sharing knowledge, best practices, and innovative resource-efficient manufacturing approaches drives progress.

By implementing these strategies and methodologies, bionic production can optimise resource efficiency and minimise waste generation, thereby fostering a bioeconomy approach (Figure 2). These practices contribute to the sustainable and circular use of resources, aligning with the principles of the bioeconomy and promoting a more environmentally conscious and resource-efficient production system.

3.4. Economic Feasibility and Market Potential

The analysis of the chosen articles encompassed an investigation into the economic viability and market potential of bioeconomy-infused bionic production. Throughout the examination of these research papers, a careful evaluation of the scalability of sustainable manufacturing methods was conducted, with a recognition of the necessity for further research and investment to overcome existing obstacles and fully exploit the market prospects associated with bioeconomy-integrated bionic production. This analysis highlights the significance of addressing various challenges, including technological constraints, cost considerations, and regulatory frameworks, in order to facilitate the widespread adoption and implementation of sustainable manufacturing techniques. By scrutinising these factors, the aim was to derive insights into the advancements and opportunities that arise from the incorporation of bioeconomy principles in bionic production.

The adoption of bio-based materials and sustainable manufacturing techniques should not only be environmentally beneficial but also economically viable. Evaluating the economic aspects helps determine the viability of bioeconomy-integrated bionic production and its attractiveness to various stakeholders, including manufacturers, investors, and consumers.

Stakeholders’ insights into economic viability, market opportunities, and potential challenges associated with integrating bioeconomy principles in bionic production address, but are not restricted to, the following aspects:

- Cost-effectiveness of Bio-based Materials: Analysing the cost-effectiveness of bio-based materials compared to their petrochemical-based counterparts is essential. Factors like feedstock availability, production costs, and market demand influence their economic competitiveness (Colorado et al. 2020). This evaluation aids in assessing the financial feasibility of bioeconomy-integrated bionic production.
- Scalability of Sustainable Manufacturing Techniques: Evaluating the scalability of sustainable manufacturing techniques, such as additive manufacturing and biofabrication, is essential. Factors like production capacity, process efficiency, equipment costs, and potential scaling barriers need thorough examination to estimate economic potential and market adoption (Sculpteo 2021).
- Market Demand and Consumer Acceptance: The success of bioeconomy-integrated bionic production hinges on understanding market trends, consumer preferences, and regulatory frameworks (Swain and Kharad 2021). Insights into environmental awareness, sustainability certifications, and government policies can help gauge market demand and potential acceptance of bio-based products.
- Economic Analysis and Business Models: Conducting economic analyses and developing robust business models are vital steps in evaluating the financial feasibility of bioeconomy-driven bionic production. Considerations include costs, revenues, return on investment, and profitability (Mishra et al. 2021). Well-defined business models aligned with bioeconomy principles and sustainability values attract investment and ensure long-term success.
- Policy and Supportive Measures: Government incentives, funding programmes, and supportive regulations play a pivotal role in fostering the economic viability and market potential of bioeconomy-driven initiatives. Understanding the policy landscape and government support levels helps identify opportunities and potential challenges in the market (Mishra et al. 2021).

By evaluating the economic feasibility and market potential of bioeconomy-integrated bionic production, stakeholders can make informed decisions about investment, technology adoption, market entry strategies, and product development (Todd 1986). Economic considerations need to be aligned with sustainability objectives to ensure the long-term viability and success of bioeconomy-driven initiatives.

The conceptual framework for implementing bioeconomy principles in the bionic product life cycle includes key components for sustainability and resource efficiency:

1. Renewable Biological Resources: Emphasises the utilisation of renewable biological resources, assessing their availability and suitability for bionic production.
2. Sustainable Design and Manufacturing: Promotes sustainable design and bio-inspired manufacturing techniques to enhance resource efficiency. It encourages the development of bio-inspired designs, additive manufacturing techniques, and biofabrication methods to enhance resource efficiency, minimise waste generation, and optimise production processes (Cherepanov et al. 2021; Schumacher et al. 2020).
3. Life Cycle Thinking: Considers the entire life cycle of bionic products, conducting assessments to evaluate environmental impacts (Moosavi et al. 2021). It emphasises the importance of conducting life cycle assessments (LCA) to evaluate the environmental impacts of bioeconomy-integrated bionic production, including factors such as energy consumption, greenhouse gas emissions, and water usage.
4. Bioeconomy Approach: Encourages waste reduction, recycling, and circular design strategies to minimise resource consumption. Circular design strategies, such as modular designs or disassembly-friendly products, are also advocated to enable easier repair, remanufacturing, or recycling.
5. Stakeholder Collaboration: Encourages waste reduction, recycling, and circular design strategies to minimise resource consumption (Deloitte 2023; Kreuzer et al. 2018).

6. Economic Feasibility and Market Potential: Considers the economic aspects, including cost-effectiveness and market potential, of bioeconomy-integrated bionic production.

Figure 3 illustrates a conceptual framework that outlines key elements for the integration of bioeconomy principles in bionic production. The framework encompasses six interconnected elements: Renewable Biological Resources, Sustainable Design and Manufacturing, Life Cycle Thinking, Bioeconomy Approach, Stakeholder Collaboration, and Economic Feasibility and Market Potential. The circular layout emphasises the cyclic and interdependent nature of these elements, highlighting the flow and connections between them. This conceptual framework serves as a guide for understanding and implementing sustainable practices, resource efficiency, and stakeholder collaboration in the development and production of bionic products.

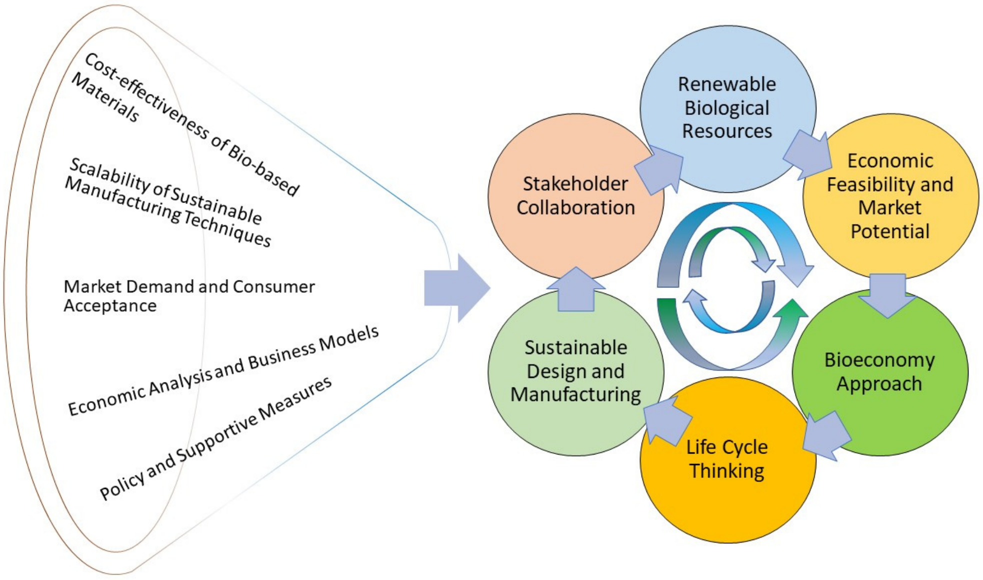

Figure 3. Conceptual framework for bioeconomy-integrated bionic production. Source: authors.

By integrating these key elements, the conceptual framework provides guidance and direction for implementing bioeconomy principles throughout the bionic product life cycle. It ensures a holistic and systematic approach to enhance sustainability, resource efficiency, and environmental performance in bionic production processes.

Policymakers can promote bioeconomy principles in industries like biotech by taking essential steps to foster sustainability and resource efficiency (Tõnnisson and Schmerber 2018). These steps include:

- Policy Coherence and Stability: Ensure stable and coherent policies that offer clarity and predictability, reducing uncertainty and encouraging long-term investments in bioeconomy initiatives.
- Financial Incentives: Provide incentives like grants, tax benefits, or financial aid to ease the transition to bioeconomy practices, making them economically viable.
- Research and Development Support: Allocate resources to support bioeconomy-related research and development, driving innovation and technological advancement.
- Standards and Certification: Set clear sustainability standards and certification systems, motivating industries to meet these criteria and boost product marketability.
- Public Procurement: Use government purchasing power to support bioeconomy products, creating demand for sustainable options and incentivising industry alignment.
- Education and Awareness: Promote bioeconomy benefits and provide education on sustainable practices to encourage a culture of sustainability.

- Public-Private Partnerships: Collaborate with private sector, research, and NGO stakeholders to accelerate bioeconomy adoption through knowledge sharing and innovation.
- Innovation Clusters and Incubators: Establish bioeconomy-focused innovation clusters and incubators to nurture startups and businesses, providing resources and mentorship.
- Regulatory Flexibility: Consider adaptable regulations to accommodate innovative bioeconomy technologies, allowing experimentation and scaling without rigid constraints.
- Commitment to Sustainability: Demonstrate a long-term commitment to bioeconomy principles, instilling confidence in businesses and investors to invest sustainably (Okada et al. 2022).

By implementing these steps, policymakers can create an enabling environment that encourages businesses and industries to adopt bioeconomy principles in their operations. Such measures will not only drive sustainability and resource efficiency but also contribute to economic growth and a more resilient and environmentally friendly economy.

3.5. Case Studies

Drawing upon the proposed conceptual framework, notable case studies from the literature were analysed, including 3D printing, short-rotation coppice (SRC)-based dendromass production, and the potential of waste biorefinery as a sustainable bio-based circular bioeconomy. These case studies were selected to provide practical insights into the implementation of bioeconomy principles in diverse fields of bionic production. While primary data collection was not conducted, these case studies were critically evaluated and used as support to develop and validate innovative strategies and frameworks.

The case study, provided by Fürtner et al. (2021), explores the integration of bioeconomy principles within bionic production, focusing on SRC-based dendromass production in Eastern Slovakia. One significant takeaway from this study is the recognition of the importance of tailoring indicators to specific regional and sectoral contexts within the bioeconomy domain. Unlike a one-size-fits-all approach, the study underscores the need for context-specific indicators that account for the distinctive characteristics of the geographical context and micro-regional scale. These factors significantly influence the selection of social indicators.

The study emphasises the role of stakeholder engagement as a key element in indicator selection for social life cycle assessment (SLCA). While previous research has suggested stakeholder involvement, this case study demonstrates its practical relevance. Notably, the findings reveal a particular focus on aspects related to workers' health and safety, working conditions, and the well-being of local communities in the survey responses.

Interestingly, societal aspects receive less priority in this case study, indicating variations in stakeholder preferences. This underscores the significance of involving stakeholders, as their input helps identify the most relevant social dimensions, ensuring a comprehensive assessment of social sustainability in the context of bioeconomy-driven production.

Moreover, the case study highlights the role of regional economic development as a pertinent aspect. Survey participants placed importance on regional value creation and economic growth. This aspect may not have been as evident in the existing literature, but it underscores the significance of considering regional and local nuances in social sustainability assessments.

Additionally, the study on waste biorefinery by Leong et al. (2021) underscores the profound global challenges associated with environmental degradation and food security. These challenges have catalysed a worldwide response from governments, non-governmental organisations (NGOs), scientific communities, and academia to seek progressive solutions.

This study highlights the pivotal role of waste biorefinery and its integration within a circular bioeconomy as a potent response to these pressing issues. An ever-changing climate, primarily driven by rapid industrialisation and urbanisation, poses a significant threat to food crop production and exacerbates environmental concerns. These activities release substantial levels of greenhouse gases (GHGs), particularly CO_2 emissions, into the atmosphere, contributing to the dire consequences of climate change, including sea level rise and disruptions in food production.

The research by Leong et al. (2021) posits that waste biorefinery, intricately linked with circular bioeconomy principles, embodies a sustainable, low-carbon solution with the capacity to mitigate these global issues. It emphasises the transformation of diverse waste materials into high-value bio-based products and energy, aligning with the core tenets of resource efficiency and waste minimization. This approach, frequently known as "waste-as-value" or "zero-waste," presents an ecologically friendly means of waste disposal and encourages a green and economical waste management strategy.

Furthermore, the study demonstrates that the valorisation of waste and side streams into bioprocesses for the production of value-added bioproducts, such as biopolymers and biofuels, holds the potential to supplant fossil fuels as a production feedstock. This shift ensures a sustainable and environmentally friendly carbon flow. The bio-based products resulting from this approach exhibit environmentally benign properties, including non-toxicity, biodegradability, and biocompatibility. This not only supports eco-friendly initiatives but also fosters a greener global environment.

In a practical context, addressing environmental concerns such as global warming, water and environmental pollution, waste disposal, and natural resource depletion becomes feasible through the adoption of circular bioeconomy strategies. For instance, the development and widespread use of bioplastics or biopolymers, replacing conventional petrochemical plastics, possesses the capacity to substantially diminish plastic pollution and its detrimental effects on soil and marine ecosystems.

Additionally, the study emphasises the importance of efficient wastewater treatment in contributing to water pollution mitigation. Integrating bioprocesses into wastewater treatment, particularly biological wastewater treatment, has demonstrated remarkable effectiveness in bioremediating various forms of wastewater, including sewage and industrial wastewater. Moreover, the sustainability of water resources can be bolstered through the cultivation of live microorganisms like bacteria, algae, and yeasts in wastewater, aiming to produce value-added bio-based products.

Another vital aspect highlighted in this case study is the production of bioenergy and biofuels from microorganisms. Unlike petroleum-dependent processes, these bioenergy production methods offer energy security while reducing GHG emissions. Biofuels, when used for various purposes like transportation fuels, can significantly contribute to GHGs' mitigation and effective carbon management.

By valorising waste into valuable bioproducts, this case study promotes a circular bioeconomy that reduces GHG emissions and environmental impacts, ultimately contributing to environmental stability and food security. This waste biorefinery–circular bioeconomy strategy offers promising prospects for a sustainable and green world, advocating for its widespread adoption as a potent solution to pressing global issues.

In the realm of bioeconomy principles, Tyrer-Jones' (2023) study sets the stage for transformative breakthroughs in 3D bioprinting, epitomising the utilisation of renewable biological resources, sustainable manufacturing techniques, and circular design strategies. This research focuses on pioneering methods aimed at elevating the functionality and performance of 3D bioprinted structures, all in alignment with broader objectives fostering sustainability and environmentally friendly production processes.

One of the key innovations in this study revolves around enhancing the biological functionality of 3D-printed cells and tissues. While volumetric bioprinting, coupled with specialised gels, accelerates the 3D printing process, it traditionally falls short in terms of precise manipulation and placement of cells where needed. Furthermore, these gels have historically lacked the flexibility to support the development, growth, and specialisation of cells.

Tyrer-Jones' research team tackled this challenge by enabling chemical modifications to the 3D-printed materials post-bioprinting. This was achieved by adjusting both the porosity of the gel and the internal compounds binding with other molecules within the gel. Such alterations enabled the integration of growth factors or bioactive proteins into the 3D bioprinted tissue, representing a significant stride towards the creation of biochemically editable smart materials.

The adoption of renewable biological resources, particularly cell-laden gels, and sustainable manufacturing techniques within this study yielded promising outcomes. It demonstrated the feasibility of constructing intricate tissue structures that offer multifaceted applications. However, to achieve full implementation of these advancements, further progress in bioprinting technology, material development, and rigorous assessments of safety and efficacy are paramount.

In summary, while the case studies provide real-world examples of bioeconomy principles in action, their full implementation requires continuous research, technological advancements, policy support, and collaboration among stakeholders. Addressing the challenges and limitations identified in these cases is crucial for unlocking the full potential of bioeconomy-driven approaches in biotech production and realising their widespread benefits. As the field of bioeconomy continues to evolve, ongoing efforts to address these factors will be essential for achieving sustainable and environmentally friendly biotech practices.

As a result of this research, innovative solutions have been proposed to enhance sustainability and environmental performance in bionic production, thereby bridging the gap between existing knowledge and real-world applications (Figures 1–3). These findings emphasise the need for further research and empirical validation to comprehensively grasp the environmental, economic, and market implications of integrating bioeconomy principles into bionic production.

4. Discussion

The integration of bioeconomy principles into biotechnology practices represents a profound paradigm shift towards sustainability and environmental responsibility. This transformative endeavour has revealed a spectrum of insights, challenges, and opportunities at the intersection of bioeconomy principles and biotech applications.

4.1. Environmental Impact and Circular Bioeconomy

Bioeconomy principles bring a host of valuable additions to current practice in biotech. By advocating for the integration of renewable biological resources and bio-based materials, the bioeconomy approach offers a transformative shift away from reliance on non-renewable fossil fuels and petrochemical-based materials. This transition enables biotech industries to substantially diminish their environmental footprint, decrease greenhouse gas emissions, and play a role in alleviating climate change.

Another critical gap that bioeconomy principles address is the lack of emphasis on circularity and waste reduction in biotech production. Current practices often lead to significant waste generation and inefficient resource utilisation. Bioeconomy principles advocate for waste valorisation, recycling, and the creation of closed-loop systems that minimise waste generation. By adopting circular design strategies and implementing waste-to-value approaches, bioeconomy-driven biotech industries can enhance resource efficiency and reduce their environmental footprint.

4.2. Economic Alignment and Sustainability

In the past, conventional biotech practices often favoured immediate economic benefits at the expense of long-term environmental consequences. Bioeconomy principles, on the other hand, endeavour to align economic and environmental objectives, illustrating that sustainable approaches can yield both economic prosperity and environmental conservation. Through the integration of economic feasibility assessments alongside sustainability considerations, these principles promote a more conscientious decision-making framework within the biotech sector (Redwood 2021; Leong et al. 2021).

Additionally, the bioeconomy framework emphasises the significance of comprehensive life cycle assessments (LCAs), which enable a holistic assessment of the environmental effects of bionic production. By considering the entire life cycle of products, including energy consumption, greenhouse gas emissions, and water usage, bioeconomy principles enable biotech industries to adopt a more environmentally responsible approach and make well-informed choices about sustainable practices.

4.3. Challenges in Implementation

The analysis of the integration of bioeconomy principles in bionic production has shed light on several gaps in current practice and identified promising perspectives for future research. These gaps and research prospects are critical for advancing sustainable and resource-efficient manufacturing processes in biotech and related industries.

Identified lacunae in current practice encompass:

1. Insufficient Adoption of Sustainable Manufacturing Techniques: Despite the promising potential, the widespread incorporation of sustainable manufacturing techniques, such as additive manufacturing and biofabrication, remains notably limited within the current landscape of biotechnology. Substantial barriers to adoption include inadequate awareness, high initial investment costs, and the need for further research to optimise and tailor these methods to specific applications.
2. Data Scarcity for Comprehensive Life Cycle Assessment (LCA): Conducting thorough life cycle assessments for bioeconomy-integrated bionic production poses significant challenges due to the scarcity of pertinent data concerning the environmental impacts of bio-based materials and sustainable manufacturing processes. To enhance the credibility and precision of LCA studies, concerted efforts should be directed towards gathering accurate and reliable data.
3. Evaluating Economic Viability and Market Acceptance: The comprehensive assessment of the economic feasibility of bioeconomy-driven bionic production demands further exploration. Although the prospects are promising, it is crucial to rigorously evaluate the viability of bio-based materials and sustainable manufacturing techniques, taking into consideration production costs, market demands, and the complexities inherent in supply chain management.
4. Technological Constraints and the Imperative for Standardisation: The current landscape encounters notable technological limitations when attempting to scale up sustainable manufacturing techniques. Ensuring seamless integration across diverse industries necessitates robust standardisation efforts concerning bio-based materials and processes, facilitating compatibility and interoperability.

Nevertheless, implementing bioeconomy principles in biotech production presents challenges that require careful attention. Overcoming technological limitations and scaling up sustainable manufacturing techniques necessitate innovative and advanced solutions, which may require substantial research and investment. The economic viability of bioeconomy-driven practices should be ensured by addressing higher upfront costs and providing incentives for businesses to adopt sustainable approaches.

Addressing these challenges requires a coordinated effort from the scientific community, policymakers, industry leaders, and consumers. By acknowledging and actively working to overcome these obstacles, the integration of bioeconomy principles in biotech production can significantly contribute to a more sustainable and environmentally conscious future.

4.4. Role of Policy Frameworks

Policy and regulatory frameworks play a vital role in incentivising the adoption of bioeconomy principles. Supportive policies, such as financial incentives and clear guidelines for sustainable practices, stimulate investment and drive innovation. However, inconsistent policies may create disincentives, hindering the transition to a bio-based and circular economy. Policymakers must establish stable, supportive, and forward-looking policy frameworks to foster innovation, sustainability, and economic growth. One way the policy environment affects incentives is through financial incentives and funding programs. Governments can offer financial support, grants, or tax incentives to companies and research institutions that invest in bioeconomy-driven initiatives. Such incentives can offset the initial costs associated with transitioning to bio-based materials or sustainable manufacturing techniques, making these practices more economically attractive.

Additionally, policies that promote research and development (R&D) in the field of bioeconomy can drive innovation and technological advancements. Governments can allocate funding to support R&D initiatives, collaborative projects, and technology transfer programmes, fostering the development of new and more efficient bio-based materials, manufacturing processes, and bioeconomy-driven solutions. Standardisation bodies can establish compatibility and interoperability standards for bio-based materials and processes to ensure seamless integration across industries.

Moreover, international agreements and trade policies can influence the global market for bioeconomy products. International cooperation and trade agreements that promote sustainable practices and eco-friendly products can create market opportunities and incentives for companies to embrace bioeconomy principles to access international markets.

On the other hand, uncertain or inconsistent policies can create disincentives for businesses to invest in bioeconomy-driven approaches. Industries may be hesitant to commit resources to research and development or change their existing practices if the policy landscape is uncertain or subject to frequent changes. Inconsistent policies may also create regulatory barriers or make it difficult for businesses to predict the long-term economic viability of bioeconomy-driven initiatives.

4.5. Future Research and Progress

Future research should focus on developing advanced bio-based materials, advancing circular design strategies for more efficient waste management, and investigating the socioeconomic impact of bioeconomy integration. Collaboration, knowledge sharing, and the intersection of biotechnology with artificial intelligence offer exciting avenues for optimisation. Understanding market demand and consumer preferences for bioeconomy-driven products will inform market strategies, and education and workforce development programmes will equip the next generation with the skills necessary for bioeconomy-integrated bionic production.

5. Conclusions

In conclusion, this research paper focuses on the integration of bioeconomy principles into bionic production processes and their impact on sustainability and environmental performance. The key findings underscore the benefits of using renewable biological resources, embracing sustainable manufacturing techniques, conducting comprehensive life cycle assessments, and evaluating economic feasibility and market potential.

The research highlights the pivotal role of bio-based materials in reducing dependence on non-renewable fossil fuels and mitigating climate change. Sustainable manufacturing techniques, such as additive manufacturing and biofabrication, exhibit their potential to enhance resource efficiency and reduce waste generation in bionic production. The discussion on life cycle assessment underscores the necessity for a thorough evaluation of the environmental impacts of bioeconomy-integrated bionic production.

Furthermore, the paper underscores the significance of economic feasibility and market potential. It stresses the importance of assessing the cost-effectiveness of bio-based materials and the scalability of sustainable manufacturing techniques. Additional economic analysis and market studies are deemed necessary to fully grasp the economic implications and commercial viability of bioeconomy-driven approaches.

The inclusion of real-world case studies within this paper is instrumental in showcasing the practical implications of integrating bioeconomy principles into bionic production processes. These case studies highlight the substantial potential for achieving outcomes that prioritise sustainability and environmental consciousness.

The integration of bioeconomy principles in bionic production offers significant opportunities to enhance sustainability, resource efficiency, and environmental performance. By harnessing renewable biomaterials, embracing sustainable manufacturing practices, and embracing the tenets of the bioeconomy, bionic production has the potential to foster a more environmentally conscious and efficient future. The seamless integration of bioeconomy principles in bionic production necessitates interdisciplinary cooperation, ongoing research and innovation, and a steadfast dedication to sustainable practices across all stages of the product life cycle.

Sustainable manufacturing techniques and processes play a pivotal role in incorporating bioeconomy principles into bionic production. By adopting techniques such as additive manufacturing, biofabrication, lean manufacturing, closed-loop manufacturing, energy efficiency, and supply chain optimisation, bionic production can achieve greater resource efficiency, minimise waste generation, and reduce environmental impact. The implementation of sustainable manufacturing practices requires collaboration, innovation, and a commitment to continuous improvement throughout the manufacturing lifecycle.

It is worth noting that conducting an LCA requires careful consideration of methodological choices, data availability, and system boundaries. As the field of bioeconomy-integrated bionic production advances, it is important to continually refine LCA methodologies, enhance data quality and availability, and incorporate evolving best practices. Methodological choices in LCA should be tailored to the specific context of bioeconomy-integrated bionic production, considering the unique characteristics of bio-based materials, sustainable manufacturing techniques, and circular design strategies. The selection of appropriate impact assessment methods, allocation procedures, and system boundaries should be based on scientific rigour and consensus.

Collaboration among industry, academia, policymakers, and financial institutions plays a crucial role in unlocking the complete economic potential of bioeconomy-integrated bionic production and facilitating the transition towards a more sustainable and resource-efficient economy.

In summary, this research provides a thorough analysis, establishes a robust framework for integrating bioeconomy principles into bionic production, and offers practical recommendations for industry stakeholders, policymakers, and researchers. It advances the understanding of bioeconomy-driven approaches, emphasising their potential to drive sustainability, resource conservation, and the transition to a bioeconomy. The paper aims to offer valuable insights for achieving environmentally conscious outcomes in bionic production, highlighting the crucial roles of bio-based materials, sustainable manufacturing, and circular design in resource efficiency and environmental impact reduction.

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