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Advancing Environmental Sustainability through a Bio-Based Circular Economy A Systematic Literature Review of Biochemical Process Engineering

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Title Page

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A Systematic Literature Review of Biochemical Process Engineering

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Abstract

This systematic literature review (SLR) synthesizes 82 Scopus-indexed, peer-reviewed articles on the bio-based circular economy (BCE) in biochemical process engineering published between 2015 and 2025, following the PRISMA protocol. These articles were reviewed using descriptive analysis and thematic synthesis that mapped publication trends, domain themes, methodological patterns, and ongoing research gaps. Results show a marked growth in publications after 2020, indicating rising global attention to bio-based solutions for environmental sustainability. The evidence base is geographically skewed toward Europe, with smaller contributions from Asia and other regions, despite the global relevance of bio-based resources. This literature focuses on the bioeconomy, circular economy, and bio-based technologies, including biorefineries, bio-based fertilizers. Thematically, the literature focuses on the bioeconomy, circular economy, and bio-based technologies, microalgae applications, and bio-based plastics. Methodologically, the corpus is dominated by quantitative techno-economic assessments, life cycle assessments, and process optimization, while the integration of qualitative, theory-based, and governance-oriented studies is still relatively limited. Conceptually, the field remains fragmented, with insufficient integration across technological, policy, and socio-ecological dimensions. To address these gaps, this literature proposes three complementary frameworks: (i) an Integrated Assessment Framework for holistic sustainability evaluation, (ii) a Multilevel Governance Framework to support BCE transitions, and (iii) a Circularity Metrics Framework that emphasizes tiered use, quality preservation, and nutrient cycling. Overall, although BCE research in biochemical process engineering is rapidly developing, future studies should strengthen the theoretical foundations, adopt interdisciplinary approaches, and develop context-sensitive frameworks to enable a more inclusive and sustainable bio-based circular transition.

Keywords: Bio-based circular economy; Biochemical process engineering; Environmental sustainability; Bioeconomy; Systematic review; PRISMA; Life cycle assessment (LCA)

1. Introduction

The transition to a bio-based economy has become an important topic for achieving environmental sustainability globally. This is in response to disasters such as climate change, depletion of fossil resources, and increasing accumulation of plastic waste. This bio-based approach allows the engineering of biochemical processes to offer promising opportunities for reducing environmental burdens and economic growth [1,2]. Study [3] highlights the potential of bio-based fertilizers to advance the principles of a circular economy, while [4] emphasizes the role of urban wasteland within this economic framework. In 2021, [5,6] expanded the discussion by integrating ecosystem services and providing a governance perspective in a bio-based circular economy. In 2022 [7,8] establishes research into microalgae technology and food waste processing as innovative pathways in the global circular economy. Meanwhile [9], talks about the development of bio-based plastics in Ukraine and [10] assesses the potential of seaweed-based products in the Mediterranean. The following year [11] introduced the concept of "libidinal economics" which is related to the bio-based economics debate. There is also research focus on circularity indicators and bio-based product design [12,13]. There are recent contributions from [14,15] which propose a more comprehensive assessment framework based on bio-based polymers, reinforcing the importance of an integrated approach in enabling the transition towards a bio-based circular economy. Overall, the literature shows an increasingly complex and multidisciplinary evolution, underscoring biochemical process engineering as a key pillar of global sustainability transitions.

1.1. Emerging Trends and Developments

Over the past decade, research on the bio-based circular economy (BCE) in biochemical process engineering has grown substantially, driven by increasing concerns about climate change, fossil resource depletion, and environmental pollution. Recent research shows a clear shift between fossil-based production systems and bio-based alternatives that emphasize resource efficiency, waste utilization, and sustainable process design [1,16]. The development of bio-based fertilizers and soil amendments is considered one of the most prominent research projects as a practical implementation of the circular economy principles [17,18]. Studies on bio-based fertilizers derived from waste streams have shown the potential to close nutrient cycles and reduce environmental impacts [3,19]. At the same time, recent research highlights that stakeholder coordination and a supportive policy

resource efficiency, waste utilization, and sustainable process design [1,16]. The development of bio-based fertilizers and soil amendments is considered one of the most prominent research projects as a practical implementation of the circular economy principles [17,18]. Studies on bio-based fertilizers derived from waste streams have shown the potential to close nutrient cycles and reduce environmental impacts [3,19]. At the same time, recent research highlights that stakeholder coordination and a supportive policy framework are critical factors in enabling the large-scale adoption of bio-based fertilizer products in circular systems [20,21].

Another major development is the increasing role of biorefineries as enabling infrastructures for BCE transitions. Integrated biorefinery systems allow the production of fuels, chemicals, and materials from renewable biomass through multiple biochemical conversion pathways [22,23]. However, despite its sustainability potential, the literature consistently reports that technology scalability and economic feasibility remain significant barriers to widespread industrial implementation [24].

In parallel, microalgae-based technologies have emerged as a rapidly growing area of research, particularly regarding waste valorization and biofuel production. Empirical and review-based studies show that microalgae systems can convert food waste, agricultural residues, and wastewater into value-added products such as biofuels and bioplastics, supporting circular bio-based systms in both urban and rural contexts [7,8].

This literature demonstrates progress in the development of biodegradable biobased materials, making them a viable alternative to conventional fossil-based plastics. Research on biobased polymers demonstrates their strong potential to reduce dependence on fossil resources. At the same time, this requires improved recycling systems and more thoughtful circular product design to ensure effective material reuse [9,15]. Recent studies on the biocircular economy (BCE) link issues of governance, ecosystem services, and circularity assessment frameworks. They emphasize that the transition to bio-based circular systems can be successful with strong coordination across multiple levels of governance.

The methodological approach also introduces practical decision-support tools that evaluate the performance of bio-based systems in terms of circularity [5,14]. These developments illustrate the growing importance of a more holistic and interdisciplinary approach. This approach combines technological innovation with existing policy, environmental, and socio-economic considerations. This BCE research highlights that biochemical process engineering has a crucial role in promoting sustainable production systems. Despite significant progress, challenges such as technology scale-up, policy alignment, and standardization of circularity metrics will not disappear immediately, thus requiring more integrated and evidence-based research in the future. Conceptual framework of bio-based circular economy in biochemical process engineering as shown in Figure 1.

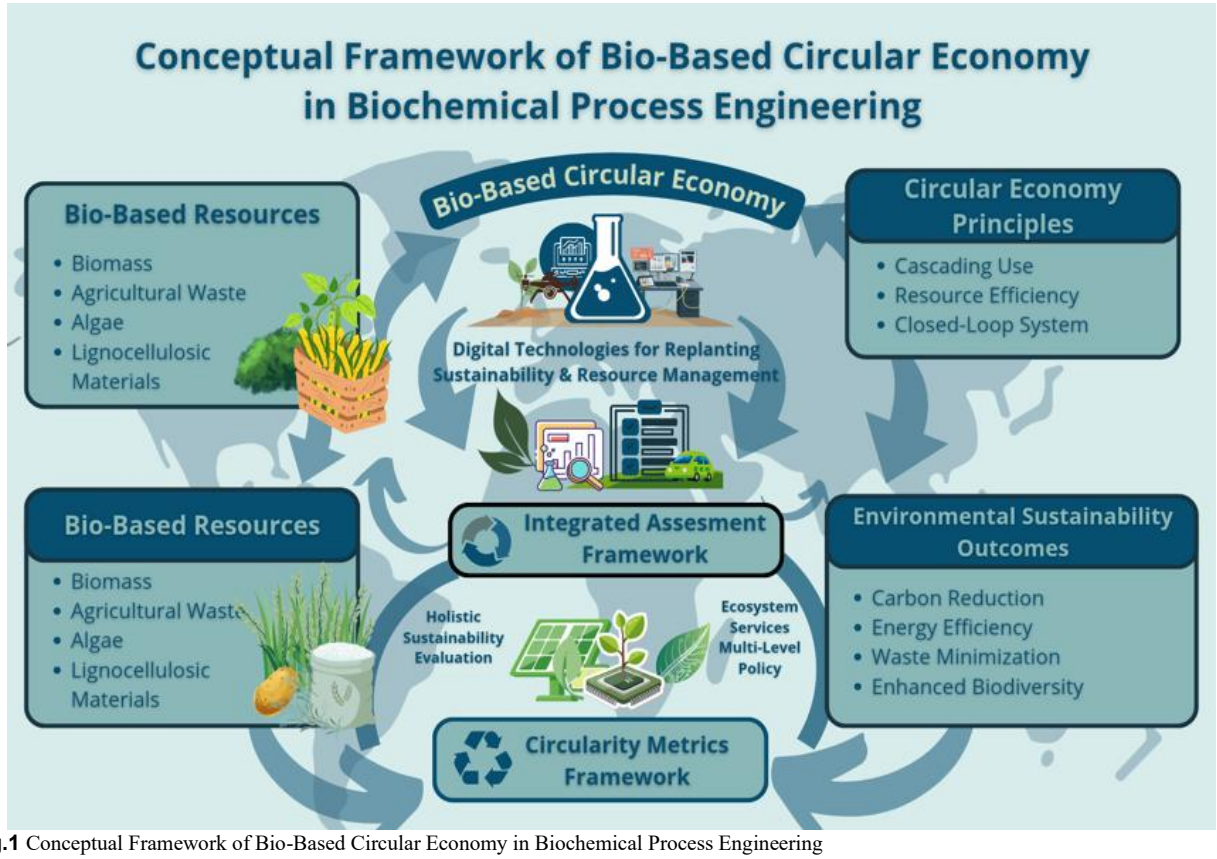


Fig.1 Conceptual Framework of Bio-Based Circular Economy in Biochemical Process Engineering

1.1. Review of Existing Research

Research studies examine important aspects of sustainability such as waste valorization and process integration in the circular bioeconomy and biochemical process engineering. The review emphasizes the development of waste biorefineries in the application of life cycle assessment, this is to evaluate environmental impacts and identifies methodological challenges, including data scarcity and limitations of non-standardized LCA, thus revealing areas for improvement in future biorefinery research [25]. In parallel, research focusing on waste biorefinery systems highlights the potential of converting diverse waste streams into value-added products, such as bioenergy and biochemicals, while also acknowledging persistent technological and economic hurdles that must be addressed for practical implementation [26]. Other studies emphasize lignocellulosic biomass as a versatile feedstock for the production of biofuels, bioplastics, and biocomposites. Lignocellulosic biorefineries could play a significant role in supporting a circular economy by utilizing waste resources and creating broader opportunities to convert biomass into valuable products [27]. Based on the literature review, research focused on sustainability, innovative waste utilization, and the development of integrated biorefinery systems is crucial. These studies also highlight other challenges, such as methodological differences between studies, limited available data, and difficulties in scaling up the technology to industrial levels. These issues indicate that this field still requires more in-depth, integrated, and empirically based research to realize its full potential.

1.2. State of the art and Identified Gaps in the Literature

Research on bio-based economy and circular economy has grown rapidly in recent years. Many scholars have conducted systematic literature reviews (SLRs). Previous reviews such as [5] and [14] organized the existing literature and approached it with a focus on ecosystem services and circular economy evaluation frameworks, but these reviews are still limited. [5] focused on European urban and suburban systems, while [14] focused on a framework that assesses biological cycles without considering different regions. Other studies [1,29] proposed an integrated indicator framework that measures biomass sustainability, but it still relies on secondary data and has not been empirically validated. Meanwhile, study [13] examined indicators of circularity of bio-based products, although the analysis did not pay much attention to quality preservation and tiered use. Generally, there are recurring issues in the aforementioned reviews. These include a lack of integrative synthesis, repeated repetition of similar themes, and a failure to classify new developments as emerging—for example, the integration of nanotechnology and artificial intelligence in the bioeconomy. Similarly, new empirical studies [7,8] reveal strong potential in waste valorization for biofuel production and algae-based applications. However, this was not fully captured in previous reviews [30,31]. To address this, SLR seeks to create a more comprehensive classification framework by integrating diverse geographic insights and exploring current issues that enable a bioeconomy transition. By offering this, this study aims to reduce thematic bias and enhance empirical relevance with robust evidence.

1.4. Identified The Novelty of The Research

Past research has made substantial contributions to the understanding of aspects of the bio-based circular economy (BCE), from biorefinery technology to practical applications such as bio-based fertilizers and microalgae [3,7]. But this research is still fragmented because it prioritizes specific dimensions without integrating social, economic, and environmental sustainability considerations in a holistic framework. In [11,32], the ecomodernist approach to bioeconomics is criticized but the analysis is limited to the philosophical and libidinal dimensions and does not examine the practical cross-sector policy implications. Likewise [1], proposes an integrated indicator framework that assesses biomass sustainability but the framework has not been tested with comprehensive empirical case studies [33,34].

A comparison of previous research reveals gaps. First, research emphasizes technological and process aspects that do not systematically integrate the multi-level policy and governance dimensions that are crucial for the feasibility of BCE transitions [5]. Second, there is limited development of comprehensive circularity metrics and indicators that capture nutrient cycles and the use of bio-based product levels [13]. Third, previous research often neglects the integration of biological and technical cycles, especially at the micro and nano levels that are relevant to the sustainability value of BCE systems [14]. Fourth, there is a lack of exploration of the social and economic dimensions of BCE—the role of local communities and bioplastic innovation startups [9,35,36].

In response, this study synthesizes a diverse body of evidence into a new conceptual framework consisting of three elements: (1) an Integrated Assessment Framework, a combination of environmental, social, and economic indicators that evaluate sustainable BCE; (2) Multi-Level Governance Framework, integrating government, industry and community regulations in support of BCE transition; (3) Circularity Metrics Framework, operational tiered use, quality preservation, and nutrient cycle of bio-based products. This framework not only broadens the analytical scope but also provides conceptual tools for application in sectoral and geographical contexts.

For example, in relation to bio-based fertilizers and microalgae, the synthesis identifies interdependencies among bioremediation technologies, circular-economy policy instruments, and local community participation in optimizing the valorization of agricultural and aquaculture waste streams [8,37]. In addition, this study proposes managerial strategies to enhance the scalability of bioplastics technologies through the integration of nanocomposites and green manufacturing routes [15]. The proposed conceptualization also offers cross-sector policy implications by recommending the development of collaborative innovation platforms involving governments, industry, and local communities to accelerate BCE technology adoption [9].

Based on theoretical contributions, this study proposes three new conceptual frameworks and repositions selected insights by introducing libidinal economic dimensions into practical policy discussions [11, 38]. Practically, these frameworks can be used as guidelines for governments, industry, and communities in strategically designing effective and sustainable BCE implementation.

Study [39] examined the effectiveness of bioaugmentation and microremediation for decontamination of exposed sediments using a laboratory method. Similarly, [40] used a multi-analytical method to extract and characterize the properties of natural dyes from Chrozophora tinctoria. This approach yielded new empirical evidence.

Second, research that develops new decision-making frameworks or tools is considered original research. Study [14] developed a 3D framework for circular economy assessment and decision support that helps stakeholders choose the right approach. Likewise, [4] proposed a bio-based framework that analyzes land-use options in urban wasteland locations, a new contribution to the circular economy literature. Although conceptual, the proposed framework provides a theoretical foundation that can be used in further research.

Third, studies using system modelling or simulation approaches are classified as original research, such as [7], which explores food waste as a medium for growing microalgae for biofuel production with a polygenerational approach in a circular economy. This modelling allows for scenario simulation and identification of large-scale challenges and opportunities. In addition, [24] applied system modelling as an evaluation of biorefinery performance in the bio-based economic transition. This has resulted in new insights that inform process optimisation and strategic planning for biorefinery development.

Fourth, research that provides analysis of a critical approach is considered original research when it provides new insights or alternatives. Such as [11] who offers a philosophical critique of bioeconomic ecomodernism and introduces the concept of libidinal economics as an alternative to the limitations of technology-centered solutions [11]. This critical analysis contributes to incorporating social and psychological dimensions into discussions of sustainability technologies.

Finally, studies that synthesize literature with a specific contextual focus or that propose new indicators may also be classified as original research. For instance, [1] proposed an integrated indicator framework to assess biomass sustainability in bio-based economy transitions [1]. Although grounded in a review-based approach, the development of new indicators provides an analytical tool that can be applied in subsequent empirical research. Similarly, [13] conducted a systematic review of circularity indicators for bio-based products and identified shortcomings in existing metrics [13]. This synthesis offers a foundation for developing more comprehensive metrics in future work.

1.5. Purpose and Scope of the Review

The main objective of this paper is to propose three new conceptual frameworks that address gaps in the Bio-based Ecosystem Engineering (BCE) literature. First, the Integrated Assessment Framework integrates environmental, social, and economic indicators to holistically evaluate the progress of BCE systems. Second, the Multilevel Governance Framework combines coordinated government, industry, and community regulations to support the BCE transition. Third, the Circularity Metrics Framework addresses the multi-level operational, quality preservation, and nutrient cycles of bio-based products. These frameworks are analytical designs applied across sectoral and geographic contexts and offer practical guidance for government, industry, and communities.

The expected contribution of this SLR is to provide a stronger and more comprehensive theoretical foundation for BCE research, while also revisiting selected prior insights by introducing additional dimensions such as the libidinal economy into practical policy discussions. From an applied perspective, this SLR is intended as a reference for stakeholders in designing more effective and sustainable BCE implementation strategies to foster cross-sector collaborative innovation. This review not only addresses critical literature gaps but also offers policy implications and accelerates a just and sustainable managerial transition to a bio-based circular economy.

2. Literature Review

The term bio-based economy refers to an economic system that utilizes renewable biomass resources to produce energy, chemicals and environmentally friendly products, thereby reducing dependence on fossil fuels [1]. This concept has developed in response to environmental challenges and the increasing need for sustainability, with a focus on optimizing biomass utilization through biorefinery technology and circular systems [24]. Since the beginning of the 21st century, the bio-based economy has evolved from being viewed primarily as a technology-centered approach to a broader conceptual framework encompassing social, environmental, and economic dimensions.

2.1. History of Research Topics

Research on bio-based economies has grown substantially over time, driven by the global imperative to reduce reliance on fossil fuels and advance environmental sustainability. In the early 2020s, scholarly attention centered primarily on identifying biomass feedstock potential and advancing biorefinery development for the production of chemicals, energy, and food [1,16]. Furthermore, research is increasingly shifting towards integrating circular economy principles with bio-based approaches, particularly through waste management and the development of higher value products such as bio-based plastics and organic fertilizers [3,15]. An important foundation of this trajectory is multi-level governance introduced as a supporting mechanism for the bio-based circular transition, which emphasizes coordination between government regulations, industry actions and society [5]. In addition, studies in 2023-2024 showed attention to the micro and nanotechnology dimensions of the circular bioeconomy, both the development of circularity indicators for bio-based products and the integration of microalgae technology to process waste in rural areas [8,13]. Ongoing challenges include technology scalability, empirical validation, and adequacy of policy integration [14,39]. Going forward, research is expected to prioritize more efficient and sustainable methods along with practical applications across sectors to support a more holistic circular economy transition.

2.2. Classical Theories and Concepts: Foundations for Modern Innovation

Recent studies on the bio-based economy and the circular economy reflect a variety of theoretical approaches and lenses relevant to the transition towards a more sustainable economic system. One of the fundamental concepts underlying much of this work is the circular economy, which emphasizes waste reduction, efficient resource use, and the regeneration of natural systems (Ellen MacArthur Foundation, 2015). This concept has been applied across diverse contexts, including waste management, bio-based production, and technological innovation. For example, [3] research into the use of biologically based fertilizers as part of a circular economy approach. A key strength of the circular economy framework lies in its potential to reduce dependence on non-renewable resources and promote more sustainable practices. However, the main challenge concerns the complexity of implementation, particularly regarding scalability and alignment with existing policy regimes [5].

Another frequently raised concept is the biorefinery, which converts biomass into value-added outputs such as chemicals, fuels, and energy. According to [24], biorefinery has great potential to minimize fossil fuel use, but is hampered by the high costs and technology of implementation. Study [11] introduces a libidinal economic perspective that provides a critical, technology-centered stance in a bio-based economy with an emphasis on humans wanting to shape technological solutions. This challenges ecomodernist assumptions that prioritize technical improvements without taking into account their social and ecological complexities. Although conceptually insightful, this still requires further research for its operation and integration of social and libidinal dimensions into long-term strategic paths [11].

Eco Modernization is also often discussed as an approach that prioritizes technological progress as a path to sustainability. However, research such as [1] suggests that this approach has limitations in addressing complex challenges, including land-use dynamics and the social impacts of bio-based transitions. Their work demonstrates the need for an integrated assessment framework that encompasses environmental, social, and economic dimensions to manage the trade-offs associated with biomass utilization. [8] Similarly, this study emphasizes the potential of algae-based technological innovations to support the development of a circular economy in rural contexts, although barriers related to cost and waste safety still need to be overcome. This research highlights the huge potential, while also underscoring the need for continuous innovation to increase scalability and real impact [8].

This literature shows that the concept of a circular and bio-based economy can provide a strong foundation for a sustainable economic system. However, effective implementation requires multidimensional integration of technologies, policies and public participation, as well as deeper research to address the ongoing challenges of scalability, cost, and impact [14].

2.3. Emerging Trends and New Approaches

In recent years, research on the bio-based economy and the circular economy has progressed substantially, accompanied by the emergence of innovative methods that support sustainability transitions. One prominent trend is the application of microalgae-based technologies to advance a bio-based circular economy in rural contexts. [8] showed that integrating microalgae technology into the management of agricultural, livestock and aquaculture waste streams has great potential to enable more sustainable circular systems. However, challenges related to scalability and cost remain major barriers to wider implementation. In addition, [42,43] introduce the concept of a hydrogen-based economy, positioning hydrogen as a key platform molecule for the renewable production of chemicals, energy, and food. This concept offers an innovative pathway to reduce reliance on fossil fuels and support energy decarbonization, although empirical validation at a pilot scale is still needed.

Another important approach is the use of biorefineries as a sustainable alternative to fossil-based processes. Study [24] evaluated the performance of biorefineries producing bio-based chemicals and fuels, noting the main challenges that remain with scalability and high production costs. In parallel [44] examined advances in bio-based nonwoven materials that have strong potential in reducing carbon footprint in industrial applications [45,46]. Their study underscores the need for continuous innovation in processing technologies, policy support, and recycling systems to facilitate the circular economy transition.

Bio-based approaches to waste decontamination have also attracted increasing attention. Based on a study [39], the effectiveness of bioaugmentation and mycoremediation for decontamination of sediments exposed to petroleum hydrocarbons showed success with hydrocarbons being completely removed after 28 days of incubation. Although further research is needed to confirm the performance in real-world conditions. This shows that bio-based approaches not only advance sustainability goals but also offer practical solutions to existing pollution challenges.

Overall, this innovative method has the potential to accelerate the transition to a bio-based and circular economy. However, barriers to scalability, cost, and empirical validation remain, which need to be addressed through further research. Therefore, stronger integration of these approaches into industry policy frameworks and practices can help accelerate progress towards global sustainability goals.

2.4. Emerging Trends Interdisciplinary connections

The current state of research on the bio-based economy is marked by a number of methodological advancements and trends that demonstrate the need to advance global sustainability and increasingly interdisciplinary approaches [47,48]. A major trend is the integration of circular economy principles with bio based systems, emphasizing waste management, resource recycling, and green technologies [49]. For example, article [3] and [5] explaining that bio-based fertilizers and ecosystem services in the context of a circulare economy, highlighting the potential to reduce dependence on non-renewable resources and increase environmental efficiency. Microalgae-based technologies for nutrient recovery from aquaculture and agricultural wastes are also included in this field of study, as explained by [8] and [7], which offer sustainable waste-management solutions while generating value-added outputs such as biofuels and bioplastics.

The creation of frameworks and evaluation instruments to measure sustainability and circularity in bio-based systems is another notable trend. While [13] examine circularity indicators for bio-based products and point out the necessity for broader measures that take into account aspects like quality preservation and cascading usage, [14] suggest a three-dimensional framework for evaluating the circular economy. Furthermore, [1] present an integrated indicator framework for evaluating biomass sustainability, emphasizing the value of comprehensive strategies that concurrently address social, economic, and environmental aspects [50].

Interdisciplinarity is further evident in the convergence of materials science, biotechnology, and policy research to advance bio-based and biodegradable polymers. [15] review the synthesis and applications of bio-based polymers, while [12] explore recovery pathways for bio-based plastics, highlights the role of product design in enhancing circularity. This progress is supported by innovations in biorefinery technology, as discussed by [24], which enable the production of chemicals and renewable energy from biomass

Focusing on combining green technologies, creating well-defined assessment frameworks, and collaborating every disciplinary to solve environmental and economic problems, current trends generally point to a change into sustainability in terms of production and consumption

Beyond these overarching trends, the literature also indicates a methodological and conceptual shift from classical approaches to more emerging, integrative approaches. Classical approaches remain largely confined to traditional techno-economic evaluations—for example, biorefinery studies that continue to face persistent challenges related to scalability and high productio costs [19,27,28]. In contrast, emerging approaches

increasingly integrate social, environmental, and economic dimensions in a more holistic manner, as illustrated by circular economy assessment frameworks that connect biological and technical cycles at micro- and nano-scales [14].

The effectiveness of classical approaches is often constrained by limited multidimensional integration. As an example, study that conducted on bio fertilizers, usually strengthen environmental effect without limiting the study on other factors, such as economic and social factors [3,53,54]. On the other hand, latest approachment give compact frameworks, especially on bio-based remediation study that combining the result that focusing on environmentally and economically in the decontamination of sediments that been contaminated [39]. Such approaches not only improve the effectiveness of technical solutions but also strengthen prospects for long-term sustainability.

This shift is also apparent in research methodologies. Classic study usually depends on literature based and conceptual analysis. For example, a study was proposed by joining indicator frameworks for the change from fossil based to eco-friendy with bio-based systems without giving evidence from testing [1]. Meanwhile, emerging research increasingly adopts experimental and system-modeling methods—for example, microalgae-based studies that combine laboratory experimentation with system analysis to optimize biofuel production from food waste [7,55].

In summary, emerging approaches appear better positioned to address the complexity of bio-based economy transitions by integrating technical, environmental, and social dimensions [56,57]. This is reflected in calls for further research emphasizing empirical application, scalability, and policy integration to enable more sustainable transitions [14,39].

3. Methodological Approach

By gathering research articles and related articles from Scopus, which is a well-known database for trusted articles, Systematic Literature Review was conducted to identify research gaps. This study used keywords, publications from 2016-2026, and reputable articles which indexed on Q1/Q2 articles. This study uses a PRISMA-based methodological workflow, which reflects the implementation of the SLR process through multiple structured and interconnected stages. In the first step, identification, publications pertaining to biochemical process engineering, the bio-based economy, and the circular economy are gathered through a methodical search of the Scopus database.

The next step is the scoping of the review stage, which involves matching the study's goals and analytical focus with the initial search results in order to fine-tune the review boundaries. The incorporation of bio-based circular economy principles into biochemical process engineering and environmental sustainability are directly related to the literature that is incorporated thanks to this phase. Following the establishment of the scope, the search stage begins with a preliminary screening based on abstracts and titles to weed out duplicates, irrelevant records, and articles that don't fit the fundamental eligibility criteria.

Articles that pass the first screening are subjected to a more thorough assessment using predetermined inclusion and exclusion criteria in the next selection stage. Only peer-reviewed journal papers that directly relate to the research topic and make significant intellectual contributions are kept after this examination. After that, eligible studies move on to the full-text screening phase, when entire articles are examined more thoroughly to ensure that they are thematically relevant, methodologically aligned, and appropriate in terms of content.

Articles that satisfy all requirements are verified as the last corpus of literature for study at the inclusion stage. In order to map research trends, technological foci, methodological methods, and the contribution of biochemical process engineering to environmental sustainability from a bio-based circular economy perspective, these chosen studies serve as the foundation for ensuing descriptive and thematic analysis. Methodological flow as shown in Figure 2.

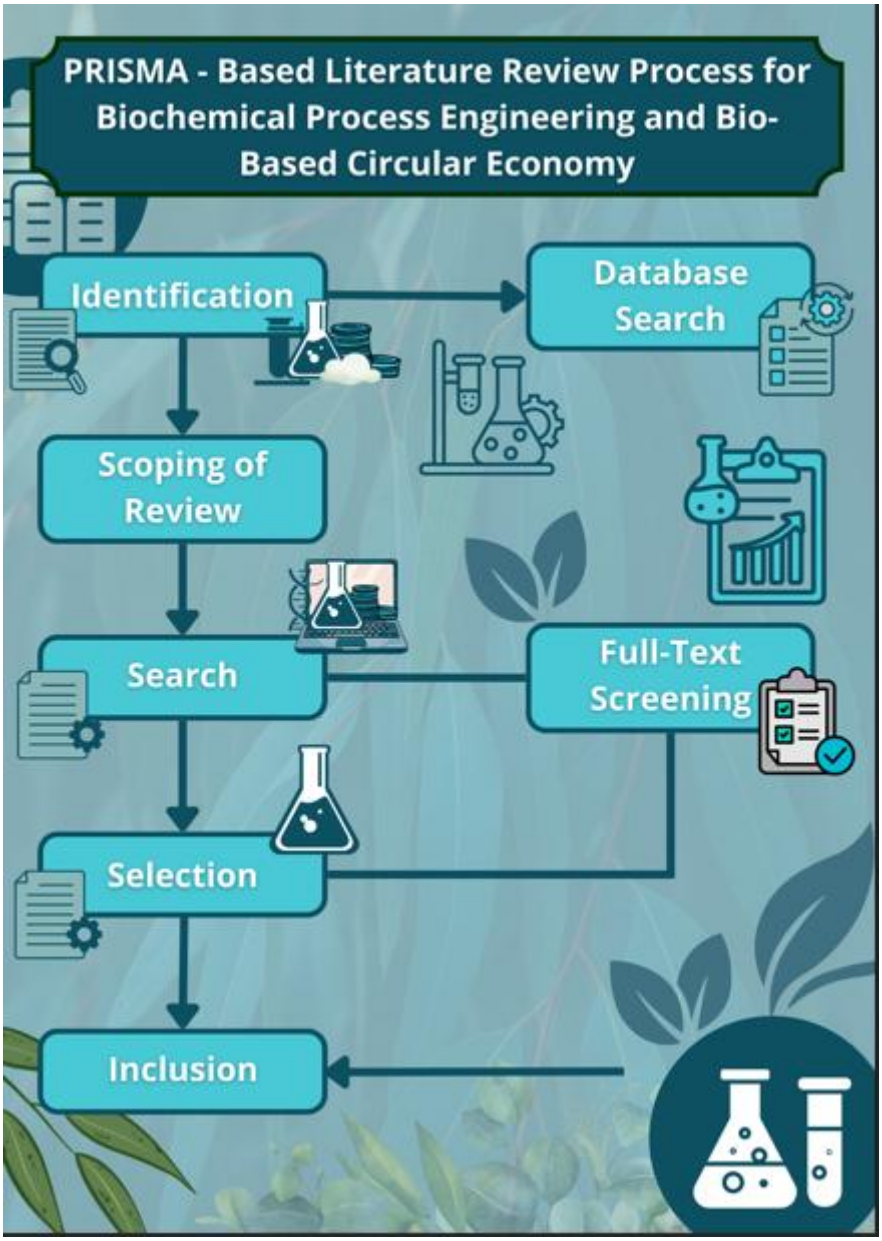


Fig.2 Methodological flow

Only articles that specifically discussed how biochemical process engineering, sustainability, or resource management intersect with the bio-based circular economy (BCE) were kept at this point. The review reduced the original pool to a more focused collection of papers that provide the theoretical and empirical basis of the study by using predetermined inclusion and exclusion criteria. A PRISMA flow diagram summarizing the results of this multi-stage screening process shows how many records were found, screened, excluded, and eventually included. After screening, 82 articles made up the final dataset. The evidence base is kept targeted, pertinent, and appropriate for additional synthesis thanks to this filtering process.

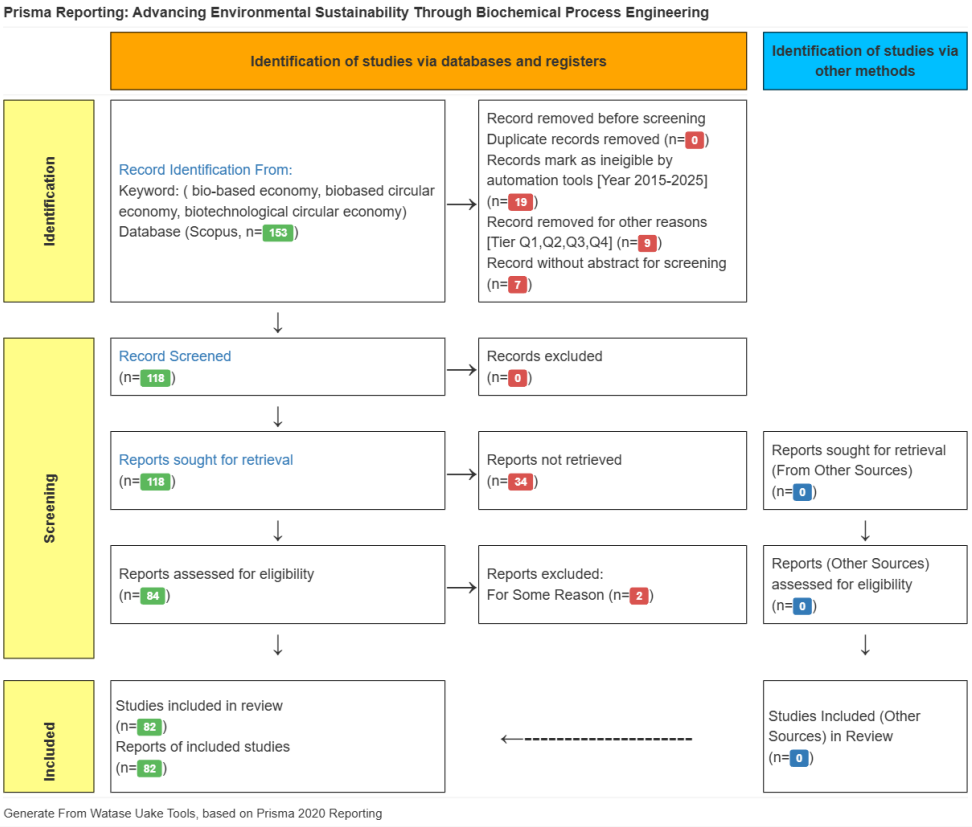


Fig.3 Identification, Screening, and inclusion steps

3.1. Research Question

In light of global issues like climate change, the reducing number of fossil fuels, and the increasing amount of plastic waste, might developments in the bio-based economy made possible by biochemical process engineering be a game-changer for attaining environmental sustainability? The creation of bio-based fertilizers for circular economy systems and microalgae-based pathways for biofuel production are two examples of the significant promise shown by research in this field thus far. Theoretical and practical ramifications of these insights are still dispersed, though, and there are still few comprehensive frameworks that combine policy design, technology innovation, and more extensive social-ecological aspects. Recent advancements, such as the use of blockchain and artificial intelligence in bio-based economic systems and the growing focus on social and ecological justice in circular transitions, highlight the need for a more thorough synthesis in order to identify research gaps and guide more all-encompassing solutions. How, however, can a methodical literature review recognize and tackle these issues in a way that promotes a quicker, more equitable, and sustainable shift to a bio-based economy?

3.2. Organization of the Paper

With regard to environmental sustainability, this study is designed to offer a thorough and methodologically sound analysis of the literature on developments in the bio-based economy made possible by biochemical process engineering. The Methodology section, which follows this Introduction, describes the Systematic Literature Review (SLR) approach, including the PRISMA principles that were used to ensure validity and transparency, the database that was utilized (Scopus), and the criteria used to choose the literature. A strong methodological basis is established in this part to bolster the findings' dependability and reproducibility. The results of the literature extraction and synthesis are then shown in the Findings section, together with research trends, important discoveries, and the gaps in earlier studies. It highlights enduring constraints while offering a thorough summary of recent advancements in the literature on the bio-based economy and circular economy. The Analysis portion then goes over the findings' theoretical and practical ramifications and suggests fresh conceptual frameworks that combine social-ecological, technological, and policy aspects. By revisiting earlier viewpoints and proposing more comprehensive strategies to handle the complexity of bio-based economy changes, this section advances scholarly discourse. In order to reinforce and broaden the study's contributions, the Conclusion concludes by summarizing the key findings, drawing conclusions about management and policy, and suggesting future research areas.

Overall, this paper is intended not only to address key gaps in the literature, but also to provide a strong theoretical and practical foundation for researchers, policymakers, and industry practitioners seeking to accelerate a sustainable and inclusive transition toward a bio-based economy.

4. Result and Analysis

The SLR's publication temporal distribution shows that, between 2015 and 2025, research on the bio-based circular economy (BCE) in relation to biochemical process engineering changed significantly. The early phase (2015–2016) saw very few articles (2 and 6 articles, respectively), indicating that research on BCE based on biochemical process engineering was still in its exploration phase. Following that, a more steady rise is seen in 2017–2018 (9 and 11 papers), suggesting that biomass usage, bioprocessing, and circular approaches are receiving greater scholarly attention in order to promote sustainability..

4.1. Yearly Article Citation

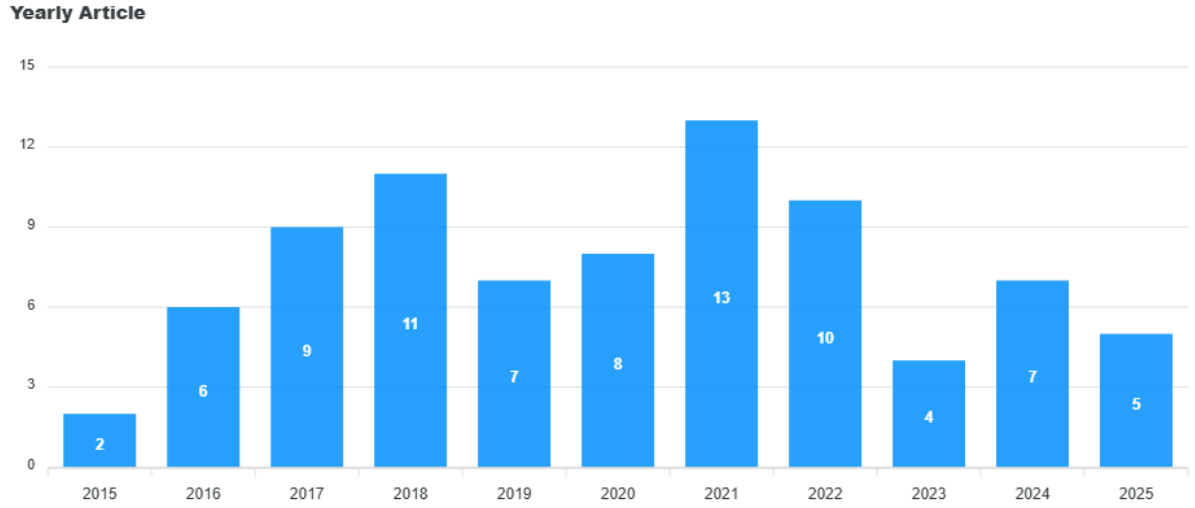


Fig.4 Yearly Article Citation

Despite a decrease in 2019 (7 articles), publication production rose once more in 2020 (8 articles) and peaked in 2021 (13 articles). A greater emphasis on research on the creation of bio-based technologies, sustainability assessment, and process optimization within frameworks for the circular economy is evident in this peak time. Publication counts declined in 2022 (10 articles) after reaching their peak, then fell even more precipitously in 2023 (4 articles), before increasing once more in 2024 (7 articles). There were only five articles published in 2025, which could be a sign of a brief drop or of insufficient coverage of the year's releases. All things considered, this pattern highlights the robust growth trajectory of BCE research in biochemical process engineering, despite occasional variations from year to year (see Fig. 4).

4.2. Country of Study and Grouping

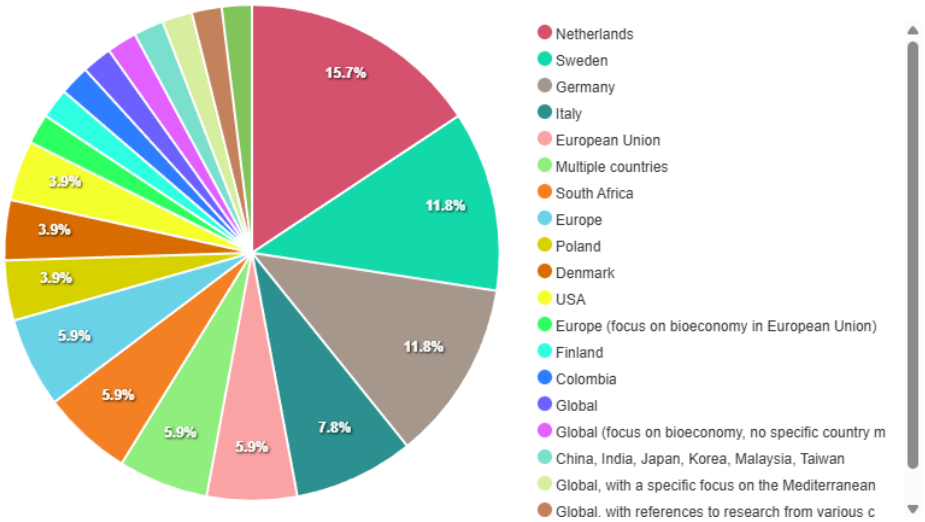


Fig.5 Country of Study and Group

Publications on the bio-based circular economy (BCE) in the context of biochemical process engineering are heavily concentrated in a few numbers of countries/regions, mostly in Europe, according to the country-level distribution study (Fig. 5). With 15.7% of all the studies, the Netherlands is the highest provider, followed by Sweden and Germany, each with 11.8%. The dominance of European nations, which are frequently bolstered by robust research infrastructures, wide-ranging collaborative networks, and comparatively robust bioeconomy and circular economy policy agendas, is further reinforced by Italy's ranking of 7.8%. In addition to single-country contributions, the European Union (about 5.9%) and the larger Europe category (roughly 5.9%) are credited with a portion of the research, indicating a cross-national focus and region-level policy framing in BCE transition talks.

Other nations' contributions are noticeable but very minor outside Europe. South Africa makes up around 5.9% of the total, while Poland, Denmark, and the USA each make up about 3.9%. This shows BCE research is not limited to one area, even if it is mostly done in Europe. There is also a category for studies that look at more than one country and studies that look at the whole world or more than one region (for example, an Asian group that includes China, India, Japan, South Korea, Malaysia, and Taiwan). This shows that countries are working together more and that sustainability problems are connected.

4.3. Country Citations

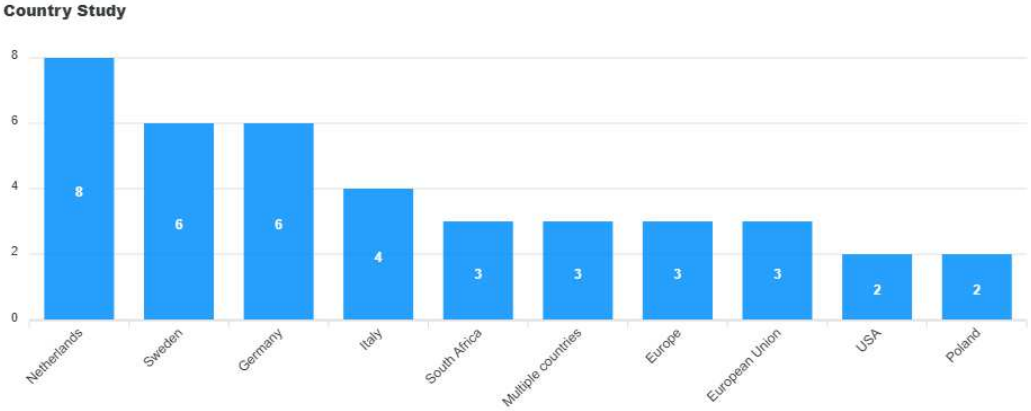


Fig.6 Country Citations

Based on Figure 6, study on bio based circular economy (BCE) that focusing on biochemical process engineering only been conducted in small amounts of countries. Netherlands as the main contributor on this study with 8 papers, followed by Sweden and Germany, both with 6 papers. Italy comes in third with four studies, demonstrating that European contributions are spread across key research centers and not confined to a single country. The only standalone country outside of America and Europe region that studied on biochemical process

is in South Africa with 3 papers. This concluded that, most of European countries with advanced technologies and infrastructures already giving significant contributions on this field of research. This also shows that most countries from this region already have clear planning and agendas for the bioeconomy and circular ecomony

Overall, this pattern suggests that although Biochemical Engineering research in biochemical process engineering is growing in many countries, the field remains concentrated in a small number of key countries/regions, primarily in Europe. This concentration raises important implications for geographic representation, as many regions with substantial biomass potential and urgent sustainability transition needs remain underrepresented in the literature. Future research would benefit from broader regional engagement to enhance the global relevance of findings and improve sensitivity to local contextual conditions.

4.4. Types of Methods Used

Despite their inconsistent application, the methodological techniques used in research on the bio-based circular economy (BCE) in the context of biochemical process engineering represent a somewhat wide mix of methodologies. The most common method, represented by 32.6% of the examined papers in Fig. 7, is literature reviews. This implies that the discipline is still developing significantly as a result of concept mapping, the synthesis of current data, and the creation of research goals. The case study technique is the second most popular strategy (15.2%), suggesting that BCE implementation in real-world contexts (such as industrial settings, biomass supply chains, or biorefinery systems) is very necessary. A significant portion (8.7%) is also accounted for by experimental techniques, which emphasize evaluating materials, processes, and biochemical technologies in controlled environments, such as laboratories.

The literature shows a greater variety of approaches with smaller proportions than these dominant methods. These include automated data analysis, systems analysis, qualitative research, and different experimental configurations (e.g., fieldwork, laboratory experimentation, and system modeling for waste/biomass valorization). In order to capture the technological, operational, and sustainability aspects of bio-based circular economy applications, BCE research in biochemical process engineering combines conceptual synthesis, implementation-oriented case studies, technical experimentation, and systems-based analysis. This diversity shows that BCE research is not limited to a single analytical lens.



Fig.7 Types of Methods

4.5. Major Publishing Journal

The distribution of publications by journal quartile (as shown in Fig. 8) indicates that research on the bio-based circular economy (BCE) in the context of biochemical process engineering is predominantly disseminated through high-reputation academic outlets. The majority of the reviewed articles (76.5%) were published in Q1 journals, suggesting that the topic has achieved strong recognition in leading journals particularly those focused on sustainability, process engineering, and bio-based innovation. This Q1 dominance also indicates that researchers position BCE as a scientifically salient area with clear practical relevance for addressing environmental sustainability challenges.

Furthermore, 19.8% of the articles were published in Q2 journals, indicating that mid to high ranking journals continue to play significant role in accommodating new ideas, technical applications, and ongoing debates in the

field. In contrast, only 3.7% of the reviewed articles appeared in Q3 journals, indicating that lower ranking journals make a relatively small contribution to shaping the main direction of BCE research in this area.

Overall, the quartile composition reinforces that BCE research in biochemical process engineering is no longer a peripheral topic, but rather part of the mainstream scientific discourse with high visibility. This pattern also reflects an academic orientation toward publishing in high-impact journals, with the expectation that such outputs will influence both scholarly development and the practical and policy dimensions of transitions toward more sustainable bio-circular systems.

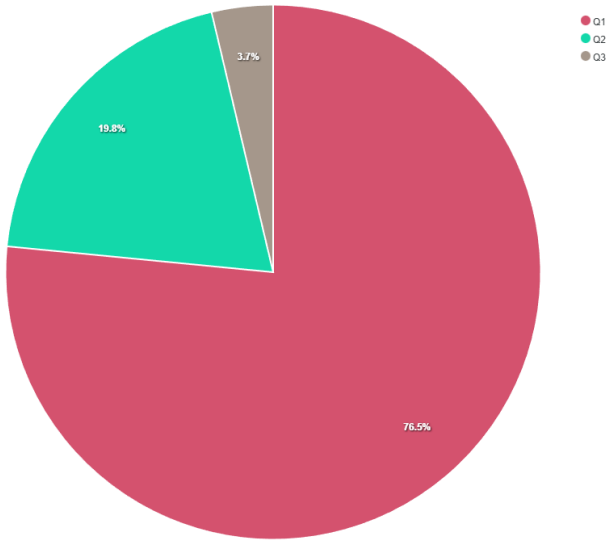


Fig.8 Percentage of Major Publishing Journal

4.6. Theory Classification

An analysis of prior studies indicates that Circular Economy (CE) theory is the most frequently adopted philosophical framework in research addressing environmental sustainability through biochemical process engineering. CE is identified in 12 of the 18 studies reviewed[1,3–5,7–10,10–14,39]. CE emphasizes principles of resource efficiency, waste minimization, and ecosystem regeneration, which align closely with biochemical research objectives aimed at developing sustainable solutions [14,58]. In addition to the circular ecomony, bioeconomic theory is also commonly applied, particularly in relation to biomass utilization and biorefinery technologies [1,24]. Citation patterns further demonstrate the strong influence of this perspective in studies addressing the global transition from a fossil-based to a bio-based economic systems [16,59,60].

Implications of this trend include increased attention to systemic approaches to addressing sustainability challenges [61,62]. CE and bioeconomy frameworks provide conceptual foundations that connect technological innovation with sustainability principles, as reflected in research on biorefineries, waste valorization, and biomaterials production [8,15]. At the same time, these studies highlight implementation challenges, including the need for multi-level policy integration and competitive economic scaling [5,63].

The relevance of this thematic direction to future challenges lies in its potential to respond to global environmental crises, such as climate change and natural resource depletion [1,64,65]. However, future research should strengthen interdisciplinary approaches and cross-sector collaboration to maximize the sustainability impact of biochemical innovations [7,66]. In this way, the topic remains not only timely but also foundational for advancing sustainable solutions amid ongoing global economic transitions. In Table 1 can be seen theoretical and methodological classifications that used in this article.

Table 1. Theoretical and Methodological Classifications

Classification	Count
Grand Theory: NA	43
Strategic Niche Management	2

Circular Economy	2
Circular Economy Theory	2
Coupled social-ecological systems framework	1
Sustainable development theory and life cycle assessment framework	1
Sustainable Blue Economy, Bioeconomy.	1
Participatory Approach	1
Libidinal economy theory by Bernard Stiegler	1
Levinass philosophy (il y a and enjoyment)	1
Green Chemistry	1
Grand theory yang digunakan: Ecological economics and circular economy theory.	1
Ecosystem Services Framework and Multi-level Governance Theory	1
Circular Economy, Bioeconomy	1
Circular Economy Theory, Biomaterials Science	1
Circular Economy Theory, Bioeconomy	1
Circular economy theory and sustainable design	1
Circular Economy and Bioeconomy	1
Bioeconomy theory and sustainable development theory	1
Bioeconomy and sustainable development	1

5. Discussion

Based on the synthesized findings from prior studies on Advancing Environmental Sustainability Through Biochemical Process Engineering, several theory-oriented recommendations can be formulated for academic researchers in this field. A key observation is the dominance of Circular Economy (CE) theory as the primary conceptual lens across most studies, with 12 of the 18 publications explicitly adopting CE [5,11,14]. This indicates that CE has become the main theoretical foundation for explaining how biochemical processes can support environmental sustainability through resource efficiency, waste minimization, and ecosystem regeneration [1,12]. Accordcakingly, researchers are encouraged not only to apply CE descriptively, but also to extend it critically-particularly by incorporating socio-economic dimensions that remain insufficiently explored in the current literature [5,11]. In addition to the circular economy, bioecomic theory plays a central role, especially in relation to biomass utilization and biorefinery development[1,24,67]. Therefore, a further theoretical recommendation is to strengthen the synergy between CE and bioeconomy through a holistic, systems-based perspective[68,69], considering that these frameworks complement each other in enabling the transition from a fossil-based economy to a bio-based economy[7,16].

Beyond theoretical integration, there is an urgent need to develop conceptual models that can accommodate complexitices of industrial-scale implementation, particularly in terms of technology scalability and multi-level policy integration [5,14,70]. Much of the existing research remains conceptual and theory-driven, dominated by systematic literature reviews and qualitative analysis [1,3], making the limited availability of empirical evidence a major constraint [8,39]. Therefore, a key recommendation is to develop theories that are not only context-grounded but also empirically testable. For example, models that integrate life cycle assessment (LCA) with a circular economy (CE)-based framework to more robustly quantify ecological impacts and evaluate sustainability outcomes [1,24]. Furthermore, theoretical approaches should explicitly incorporate local conditions, particularly in developing countries, where technologies such as microalgae systems and bioplastics have great potential but are constrained by economic and infrastructure constraints [8,9,71]. In this regard, future theory development should bridge the gap between global technological innovation and local implementation readiness, thereby supporting more inclusive and enduring sustainability transition [15,16].

5.1. Future Reaserch Directions

This Systematic Literature Review (SLR) aims to analyze and contextualize developments in research on Advancing Environmental Sustainability Through Biochemical Process Engineering, particularly within the frameworks of the circular economy and bioeconomy. The scope includes an assessment of publication trends, dominant themes, research methods, theoretical foundations, journal quartile classifications, and the geographic

and methodological contexts of 18 prior studies. The findings indicate that the circular economy and bioeconomy constitute the central thematic pillars of the literature, supported by related concepts such as biorefineries, microalgae utilization, and biochemical process–based waste management. Publication trends suggest increasing global interest since 2020, with European countries—especially those advancing policy development and circular system frameworks—dominating the corpus, while developing countries such as India and Brazil tend to emphasize localized applications and microalgae-based technologies.

Methodologically, the majority of studies adopt qualitative approaches through systematic literature review designs (14 of 18 studies), and 16 of the 18 articles are published in Q1-tier journals, indicating strong academic visibility and quality. However, a major limitation is the predominance of conceptual research and the relative scarcity of industry-scale experimental studies. Key research gaps include the integration of socio-economic dimensions, technological scalability, and multi-level policy arrangements needed to support global transitions.

Theoretically, this SLR reinforces circular economy and bioeconomy perspectives as strategic sustainability frameworks. From a practical standpoint, it highlights the need for international collaboration, technology transfer, and supportive policy frameworks to enable green innovation. Recommendations for future research include large-scale experimentation, the integration of mixed-method approaches (qualitative–quantitative), and interdisciplinary studies combining engineering, economics, and policy to accelerate transitions toward a more sustainable economy.

5.2. Theoretical Contribution

Based on the synthesized findings from prior studies on Advancing Environmental Sustainability Through Biochemical Process Engineering, several theoretically oriented recommendations can be formulated for academic researchers in this field. A core observation is the dominance of Circular Economy (CE) theory as the prevailing conceptual foundation across most studies, with 12 of 18 publications explicitly adopting CE as their primary lens [5,11,14]. This pattern indicates that CE has become the central theoretical anchor for explaining how biochemical processes can advance environmental sustainability through resource efficiency, waste minimization, and ecosystem regeneration [1,12,72]. Accordingly, researchers are encouraged not only to apply CE descriptively, but also to extend it critically—particularly by integrating socio-economic dimensions that remain underexplored in the existing literature [5,11]. Alongside CE, bioeconomy theory also plays a key role, especially in relation to biomass utilization and biorefinery development [1,24]. A further theoretical recommendation is therefore to strengthen the synergy between CE and bioeconomy through more holistic systems perspectives, given that these frameworks are complementary in supporting transitions from fossil-based to bio-based economic systems [7,16].

Beyond theoretical integration, there is an urgent need to develop conceptual models capable of accommodating the complexity of industrial-scale implementation, particularly in relation to technological scalability and multi-level policy integration [5,14,73]. Much of the current evidence base remains conceptual, with systematic literature reviews and qualitative analyses dominating the methodological landscape [1,3], which contributes to a persistent lack of empirical validation [8,39,74]. Consequently, a key recommendation is to advance theories that are not only contextually grounded but also empirically testable—for example, models that integrate life cycle assessment (LCA) with CE-based frameworks to quantify ecological impacts and evaluate sustainability trade-offs more robustly [1,24]. In addition, theoretical approaches should explicitly account for local conditions, particularly in developing countries, where technologies such as microalgae systems and bioplastics have substantial potential but are constrained by economic and infrastructural limitations [8,9]. In this regard, future theoretical development should aim to bridge the gap between global technological innovation and local implementation readiness, thereby supporting more inclusive and durable sustainability transitions [15,16].

6. Conclusion

This Systematic Literature Review (SLR) identifies dominant patterns in research on Advancing Environmental Sustainability Through Biochemical Process Engineering using the TCM framework (Theory, Context, Methodology). From a theoretical perspective, Circular Economy (CE) and bioeconomy emerge as the primary philosophical foundations underpinning the reviewed studies. CE foregrounds resource efficiency, waste minimization, and ecosystem regeneration, whereas the bioeconomy perspective emphasizes biomass utilization and the integration of biorefinery technologies. Together, these theories provide a robust conceptual basis for explaining how biochemical process engineering can contribute to environmental sustainability through systemic and holistic approaches.

In terms of geographic context, the reviewed literature is dominated by European contributions, reflecting the European Union's strong commitment to green growth and circular economy transitions. European studies frequently focus on biorefineries, bioplastics, and waste management, supported by policy environments that incentivize sustainable innovation. By contrast, research from Southeast Asia and Latin America tends to emphasize locally grounded applications such as microalgae utilization and lignocellulosic conversion reflecting the regions' natural resource endowments. This distribution suggests an imbalance between developed and developing countries, where advanced economies contribute more to globally oriented technological development, while developing countries often prioritize affordable and context-appropriate practical solutions.

Methodologically, the literature is dominated by qualitative approaches, SLR givingus information on concepts and frameworks. This approachment giving complete identification on several factors across Bio-Based Circular Economic (BCE) factors, such as trends, turbulence, and something to develop in the coming era. Several research that conducted on experiments and modeling to validate practical implications on this technology. Results on that research stated that this model is still in contention, while study using experimental and modeling design is uprisingly become necessary to develop solutions to company scales

These findings underlined the necessity on integrating several factors to obtain transitions on global sustainability, such as terms, theory, and practice. Several challenges include technologica scale-up, multi-level policy integration, and international collaboration to facilitate technology transfer from developed to developing contexts. Overall, this research domain holds significant potential to contribute to the achievement of the SDGs through biochemical innovation and circular economy oriented approaches.

Authors'contributions

Nurhayati Sembiring: Conceptualization, methodology, writing original draft Preparation.

Jhan Pranata Brahmana: Data Curation, visualization, Validation, formal Anlysis.

Akbar Gading Alfadli Harahap: writing review and editing

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Ethics approval and consent to participate : The authors declare that the study followed all relevant ethical guidelines. All participants were informed about the objectives of the study and provided their consent to participate voluntarily.

Consent to publish : All authors have read and approved the final manuscript and consent to its publication.

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