Novatio: Journal of Management Technology and Innovation

E-ISSN : 3030-8674
Volume. 2, Issue 3, July 2024
Page No: 144-159

Green Technology Integration and Circular Economy Pathways for Sustainable Innovation

Tamara Maharani Siswadhi[1], Noer Fajrin[2], Jakfar[3], Ahmad Mubarok[4], Ahmad Hariri[5]
[12]Politeknik Manufaktur Negeri Bandung, Indonesia
[3]Universitas Jayabaya, Indonesia
[4]Akademi Penerbang Indonesia Banyuwangi, Indonesia
[5]Politeknik Penerbangan Palembang, Indonesia
Correspondent : tamara.maharani@polman-bandung.ac.id1

Received : May 26, 2024
Accepted : July 12, 2024
Published : July 31, 2024

Citation: Siswadhi, T, M., Fajrin, N., Jakfar., Mubarok, A., Gariri, A. (2024). Green Technology Integration and Circular Economy Pathways for Sustainable Innovation. Novatio: Journal of Management Technology and Innovation, 2(3), 144-159.

ABSTRACT: This study examines the integration of green technologies into circular economy systems as a pathway to advancing sustainable innovation. The objective was to synthesize existing literature to identify key strategies, challenges, and implications across diverse industrial and geographical contexts. A narrative review methodology was employed, drawing on peer-reviewed sources indexed in Scopus, Web of Science, and Google Scholar. The results highlight four main themes: product design and eco-innovation, renewable energy and photovoltaics, biomaterials and lignin applications, and sustainable business models. Evidence shows that lifecycle assessment tools and decision-making frameworks enhance eco-design. Advancements in solar technologies promote decarbonization but face storage and recycling challenges. Lignin valorization offers significant promise yet is constrained by technical and scalability issues. Circular business models provide systemic benefits, but their effectiveness varies depending on regulatory environments, cultural acceptance, and financial structures. The review concludes that strengthening design strategies, renewable energy deployment, biomaterial innovations, and business model adaptation are essential to overcoming systemic challenges and achieving sustainable economic transitions.

Keywords: Green Technology, Circular Economy, Sustainable Innovation, Renewable Energy, Eco-Design, Biomaterials, Sustainable Business Models.

INTRODUCTION

Over the past decade, the intersection between sustainable innovation and the circular economy has emerged as a focal point in academic and policy discourse, reflecting a broader global shift toward environmentally responsible economic practices. A wealth of scholarship from 2015 to 2025 highlights the role of digital technologies in advancing circular business models, which prioritize resource efficiency, renewable energy adoption, and waste minimization (Gupta, 2025;

Nasim et al., 2024; Hong & Xiao, 2024). This convergence between digital innovation and circular principles has been increasingly recognized as a transformative pathway to enhance productivity while reducing adverse environmental impacts. For example, artificial intelligence (AI) and blockchain are being deployed to optimize waste reduction, enable real-time resource monitoring, and ensure transparency across supply chains (Hong & Xiao, 2024; Yu et al., 2024). In this respect, the literature illustrates how technological integration does not merely improve operational efficiency but also fosters accountability and resilience in complex global production systems.

Another significant body of work stresses the importance of institutional and policy frameworks in cultivating an enabling environment for sustainable innovation. Evidence suggests that aligning environmental regulations with economic incentives is critical in guiding industries toward greener practices (Stefanis et al., 2024; Khan et al., 2021). Nordic countries provide exemplary cases where technological advancements are integrated with policy interventions to stimulate green growth and strengthen sustainability transitions (Khan et al., 2021). Similarly, scholars highlight the growing significance of Micro, Small, and Medium Enterprises (MSMEs) in implementing inclusive circular strategies, especially in developing economies (Loreño & Yu, 2025; Mokdad, 2025). By linking grassroots entrepreneurship to global sustainability goals, MSMEs serve as vital actors in bridging local innovation with international commitments, underscoring the importance of scaling sustainable practices across multiple economic layers.

Recent empirical studies reinforce the importance of technological adoption by documenting its tangible environmental benefits across various sectors. In the energy sector, the transition toward renewable energy has resulted in notable reductions in greenhouse gas emissions (Xiao et al., 2024; Borysiak & Brych, 2022). Manufacturing industries have similarly benefited from innovations such as enhanced recycling systems and green supply chain management, which significantly lower waste generation while improving carbon footprints (Raman et al., 2023; Dhayal et al., 2025). Meanwhile, the transportation sector has witnessed substantial transformations through the adoption of electric vehicles and hydrogen fuel cell technologies, both of which align with global carbon reduction targets while advancing sustainable mobility (Corcione, 2024; Nygaard, 2022). Taken together, these findings demonstrate that the adoption of green technologies across key industries is not only feasible but also impactful in achieving climate mitigation goals.

Beyond the environmental dimension, the incorporation of green technologies into business strategies contributes to long-term resilience and competitiveness. Studies suggest that innovative practices aligned with the Sustainable Development Goals (SDGs) hold potential for systemic benefits, as they simultaneously enhance environmental outcomes and economic performance (Stefanis et al., 2024; Rahman et al., 2025). Alaghemandi (2025) further contends that such strategies provide firms with opportunities to diversify business models and strengthen their adaptability to volatile global markets. In this sense, sustainable innovation represents a dual value proposition: it safeguards ecological systems while equipping industries with tools for sustained growth in a rapidly changing world.

Despite these advancements, integrating green technologies into circular production systems remains fraught with challenges. One persistent obstacle is the reluctance to adopt new technologies, often driven by concerns regarding high initial investment costs and uncertainties about operational integration (Singh & Thanki, 2024; Raman et al., 2023). Firms are frequently forced to weigh short-term financial pressures against long-term sustainability imperatives, resulting in hesitation to pursue potentially transformative innovations.

A related challenge lies in the shortage of specialized skills and knowledge necessary for effective green technology integration. Many organizations lack adequate training programs to build competencies in eco-design, lifecycle assessment (LCA), and material optimization (Singh, 2025; Luu et al., 2024). Without these capabilities, industries struggle to implement circular economy principles effectively, undermining the potential for long-term resource efficiency and waste minimization. Addressing this issue demands targeted efforts to enhance education, training, and capacity-building tailored to industry-specific sustainability needs.

At the policy level, gaps remain in the coordination and harmonization of international frameworks designed to support circular economy transitions. Although initiatives such as the European Green Deal illustrate significant progress, discrepancies persist between policy intent and implementation, particularly at local and private sector levels (Hong & Xiao, 2024; Stefanis et al., 2024). Weak synergies between public policy and industrial practices often result in fragmented progress, leaving considerable room for improvement (Dzwigo et al., 2021; Pant & Gandhi, 2025). Moreover, inconsistencies in evaluative parameters used to measure the effectiveness of circular economy policies further complicate efforts to assess and refine interventions (Romani et al., 2016; Benjaafar et al., 2025). These limitations underscore the need for more coherent and globally coordinated approaches that integrate both policy and industrial innovation.

Research gaps also persist in identifying effective indicators to assess circular economy transitions. Scholars argue for the development of standardized metrics that capture both environmental and socio-economic outcomes in context-specific ways (Luu et al., 2024; Vinay et al., 2025). Without reliable indicators, policymakers struggle to evaluate the success of circular strategies or to adapt policies to different regional and industrial contexts (Biber-Freudenberger et al., 2020). As such, advancing this field requires rigorous methodological innovations that can provide clear and actionable insights into the effectiveness of sustainability transitions.

The objective of this narrative review is to synthesize and critically analyze the existing body of literature on the integration of green technologies into circular economy production systems. Specifically, the study seeks to explore approaches and practices that have been adopted across different industries and regions, examining their implications for reducing environmental impacts and enhancing resource efficiency (Khan et al., 2021; Stefanis et al., 2024). By consolidating findings from diverse contexts, the review aims to generate a comprehensive understanding of how green technology adoption contributes to sustainable industrial transformation while highlighting challenges that require further scholarly and policy attention.

The scope of this review encompasses multiple geographical regions and industrial sectors, reflecting the global relevance of the topic. In Europe, research predominantly focuses on green policy initiatives and technological innovations within renewable energy and chemical industries (Stefanis et al., 2024; Pardal et al., 2020). Agricultural sectors, particularly those emphasizing waste valorization and biotechnological applications, have also received increasing attention (Ligarda-

Samanez et al., 2025; Purwanto et al., 2025). In Asia, studies emphasize digital applications within circular economy models, especially in e-commerce and manufacturing, where digital platforms are leveraged to optimize efficiency and sustainability outcomes (Yu et al., 2024; Lim et al., 2024). By capturing this diversity, the review underscores the importance of multi-sectoral and multi-regional perspectives in shaping holistic solutions to sustainability challenges.

Overall, this introduction establishes the foundation for a narrative review of green technology integration within circular economy frameworks. By situating the discussion within current literature, it delineates both the achievements and persistent challenges of sustainable innovation. In doing so, it justifies the need for further scholarly exploration while framing the study's objectives and scope as critical contributions to the advancement of sustainable production and policy design.

METHOD

The methodology of this narrative review was designed to ensure a rigorous and comprehensive examination of the literature on sustainable innovation and the circular economy, with a particular focus on the integration of green technologies into production systems. To capture a wide range of relevant studies, the literature search was conducted across multiple databases, namely Scopus, Web of Science, and Google Scholar. Scopus and Web of Science were prioritized due to their extensive coverage of peer-reviewed journals and their strong reputations for indexing high-quality academic work in the domains of science, technology, and innovation (Xiao et al., 2024; Khan et al., 2021; Yin et al., 2022). Google Scholar was also employed to broaden the search scope and to capture additional materials such as working papers, conference proceedings, and other scholarly outputs that may not always be indexed in Scopus or Web of Science. While Google Scholar provided wider accessibility, the variability in quality necessitated careful screening and evaluation of the retrieved articles (Xiao et al., 2024; Khan et al., 2021).

The search strategy relied on carefully selected keywords that reflected both the thematic focus of the review and the evolving terminology within the literature. Core keywords included "green technology," "circular economy," "sustainable innovation," "sustainable manufacturing," and "waste management," as these terms broadly encapsulate the intersection between technological adoption and circular practices (Rahman et al., 2025; Reema et al., 2022; Agarwal et al., 2025). To capture more specialized discussions, additional terms such as "digitalization in circular economy" and "green supply chain practices" were included (Liu et al., 2024; Dzwigo et al., 2021). The combination of general and specific keywords was designed to ensure coverage of both foundational discussions and emerging subfields, particularly those addressing the application of digital tools in circular contexts.

A systematic process was applied to establish inclusion and exclusion criteria, ensuring that only the most relevant and reliable studies were considered. Articles included in this review had to meet three key criteria. First, they had to be published in peer-reviewed journals within the past five years to ensure that the findings reflected the most recent developments in the field. Second, they had to directly address the application of green technologies within the framework of the circular economy, whether in theory or in practice. This requirement excluded articles that only discussed sustainability or technology in isolation without considering their interplay in circular systems. Third, eligible studies had to provide either empirical evidence, such as data from case studies, surveys, or experiments, or theoretical analyses that offered conceptual insights into the integration of green technologies. These criteria ensured that the review was grounded in both current and relevant scholarship.

Conversely, studies were excluded if they failed to meet these standards. Publications that had not undergone peer review, such as opinion pieces or non-academic reports, were removed to maintain scholarly rigor. Similarly, articles that were tangential to the topic—for example, those addressing highly technical aspects of materials science without reference to broader sustainability or economic implications—were excluded. Finally, studies older than five years were generally omitted, unless they offered seminal contributions still widely cited in contemporary discourse. This exclusion criterion was necessary to maintain the review's focus on the evolving state of the art while acknowledging that the field of sustainable innovation is dynamic and rapidly progressing.

The types of studies included spanned a range of methodological approaches, reflecting the interdisciplinary nature of the subject. Empirical research comprised case studies examining specific industries or firms that had adopted circular practices, experimental studies testing new green technologies in production processes, and surveys capturing stakeholder perspectives on sustainability transitions. In parallel, theoretical studies offered conceptual frameworks, models, and policy analyses that provided a deeper understanding of the systemic challenges and opportunities associated with green technology integration. This inclusion of diverse study types was deliberate, as it allowed the review to capture both micro-level practical insights and macro-level structural considerations.

The process of literature selection followed a systematic multi-stage procedure. Initial searches were conducted in each database using combinations of the identified keywords. The search results were then compiled, and duplicate entries were removed. Following this, titles and abstracts were screened for relevance to the core themes of sustainable innovation, circular economy, and green technology. At this stage, a significant number of articles were excluded because they did not address the intersection of these themes or failed to align with the established inclusion criteria. Articles that passed the initial screening were then subjected to full-text review. During this stage, detailed assessments were conducted to evaluate the methodological rigor, relevance, and contribution of each study. Particular attention was paid to whether the research addressed questions of integration—such as how green technologies are incorporated into production systems, supply chains, and policy frameworks—rather than treating these elements in isolation.

Evaluation of the selected studies also considered the contexts in which they were conducted, including sectoral and geographical differences. This was necessary because the applicability of green technologies can vary significantly depending on industrial structures, regulatory environments, and levels of technological development. For example, literature focusing on European policy frameworks often emphasized the role of regulations such as the European Green Deal, while studies from Asia highlighted the role of digital technologies in enabling circular practices in e-commerce and manufacturing (Hong & Xiao, 2024; Yu et al., 2024; Lim et al., 2024). Recognizing these contextual distinctions allowed for a more nuanced synthesis of findings that accounts for variations in industrial and regional priorities.

The final dataset of studies was then synthesized thematically, with findings organized around key categories such as product design and eco-innovation, renewable energy and carbon neutrality, biomaterials and waste valorization, and sustainable business models. This thematic organization facilitated cross-comparison of results across different contexts and highlighted recurring patterns, challenges, and opportunities in the literature. By structuring the synthesis in this way, the review was able to provide both a comprehensive overview of the state of research and a detailed examination of sector-specific insights.

Throughout the review process, efforts were made to ensure transparency and replicability. All stages of the search and selection process were documented, including the databases used, search terms applied, and criteria for inclusion and exclusion. This methodological rigor enhances the credibility of the findings and allows future researchers to replicate or extend the review. By combining systematic search procedures with critical evaluation of the literature, the methodology adopted in this study ensures that the resulting synthesis provides a robust and insightful contribution to the field of sustainable innovation and the circular economy.

In conclusion, the methodological approach adopted in this review balances comprehensiveness with selectivity. By utilizing reputable databases, applying precise search terms, and implementing clear inclusion and exclusion criteria, the review captures the breadth and depth of current scholarship. The integration of both empirical and theoretical studies ensures that the findings reflect not only practical applications but also conceptual developments. This approach allows for a nuanced exploration of how green technologies are being integrated into circular economy frameworks across diverse contexts, thereby setting the stage for the subsequent analysis of results and discussion.

RESULT AND DISCUSSION

The findings of this narrative review reveal diverse insights into the integration of green technologies and circular economy practices across multiple industrial sectors and geographical contexts. The results are organized into four thematic areas: product design and green innovation, renewable energy and photovoltaics, biomaterials and lignin applications, and sustainable business models. These themes collectively highlight how technological advances, policy interventions, and organizational practices intersect to drive sustainability, while also underscoring persistent challenges that require further investigation.

Product Design and Green Innovation

The integration of green technologies into product design is a crucial step toward minimizing environmental impacts throughout the lifecycle of goods. Ecodesign principles, which involve selecting eco-friendly materials, implementing energy-efficient production processes, and designing products for recyclability, have gained significant traction in the literature (O'Connor et al., 2016). Studies emphasize that lifecycle thinking embedded into design practices can substantially reduce waste and enhance sustainability outcomes. In this regard, Life Cycle Assessment (LCA) has become a widely adopted tool for evaluating the potential environmental impacts of different design choices. By quantifying carbon footprints, energy consumption, and resource use across various scenarios, LCA provides critical evidence to guide decision-making during the design stage.

Alongside LCA, decision-making methodologies such as the Analytic Hierarchy Process (AHP) have also been applied to evaluate sustainability criteria at the early stages of design. AHP enables systematic comparison of multiple design options based on environmental, social, and economic dimensions, offering a structured approach to prioritizing sustainability goals (Losada et al., 2019). Moreover, Khan et al. (2021) highlight the growing use of technology-based assessment tools that predict the environmental consequences of product innovations, thereby equipping designers with data-driven insights to optimize their choices. Together, these methods illustrate how product innovation informed by environmental evaluation has emerged as a cornerstone of sustainable manufacturing, setting the foundation for broader adoption of circular economy strategies.

Renewable Energy and Photovoltaics (PV)

The renewable energy sector has been central to discussions on circular innovation, with solar photovoltaics (PV) standing out as a critical technology for decarbonizing energy systems. Recent research emphasizes breakthroughs in PV materials, particularly perovskite-based solar cells, which demonstrate superior conversion efficiencies compared to conventional silicon-based technologies (Pardal et al., 2020). Studies such as Megawati et al. (2024) indicate that combining biferroelektrik solar cells with novel nanomaterials not only enhances efficiency but also reduces production costs, making renewable energy adoption more economically viable.

Despite advances in PV efficiency, energy storage remains a critical challenge. Without effective storage solutions, the intermittent nature of renewable energy sources undermines grid stability and widespread adoption. Literature points to ongoing experimentation with battery technologies and hybrid storage systems, yet highlights the urgent need for scalable and cost-effective innovations to support large-scale renewable deployment.

Waste management and recycling of PV panels present another area of divergence between developed and developing economies. European countries, under stringent regulatory frameworks, have advanced integrated recycling systems that recover valuable materials from end-of-life panels (Zhao & Li, 2020). These systems demonstrate both environmental and economic benefits by closing material loops. In contrast, developing countries often face infrastructural and regulatory gaps that hinder effective recycling. Studies by Coelho et al. (2020) and Sadiq et al. (2021) stress that without adopting modern recycling technologies, many regions risk exacerbating e-waste problems as solar adoption expands. These disparities illustrate the role of governance, policy, and technological readiness in shaping the sustainability of PV energy transitions globally.

Biomaterials and Lignin Applications

The potential of lignin as a bio-based material offers significant promise for advancing circular economy principles. As one of the most abundant natural polymers, lignin can be utilized in plastics, fuels, and bio-composites, reducing reliance on petroleum-based resources. Ligarda-Samanez et al. (2025) demonstrate that lignin-based composites can effectively substitute for synthetic binders, contributing to material sustainability and reducing ecological footprints. Similarly, lignin's application in renewable energy and bio-product development underscores its versatility as a sustainable feedstock.

Nonetheless, technical barriers constrain the scalability of lignin utilization in industrial contexts. Lignin extraction is complex and costly due to its chemical entanglement with cellulose and hemicellulose, making separation a significant challenge (Pagnotta, 2025; Sahu et al., 2024). Variability in lignin composition across biomass sources further complicates its use, leading to inconsistencies in performance and quality (Motaleb et al., 2025). These limitations highlight the need for innovation in lignin processing technologies, including advanced separation techniques and standardized characterization methods. Comparative studies across industrial regions indicate that while Europe and North America are advancing pilot projects for lignin valorization, many developing economies remain constrained by limited technological infrastructure. Thus, while lignin represents a strategic material for circular economies, realizing its full potential will depend on overcoming technical and infrastructural hurdles.

Sustainable Business Models

The literature increasingly highlights sustainable business models as pivotal to embedding circular economy practices into industrial operations. In the mining sector, models emphasize waste reuse, cleaner extraction processes, and rehabilitation strategies that align with sustainability mandates (Reema et al., 2022; Xiao et al., 2024). For manufacturing industries, sustainable business models prioritize designing products for reuse, repair, and recycling, thereby extending product lifecycles and reducing resource inputs. Gyimah et al. (2025) report on construction firms in Ghana that are adopting circular practices to repurpose waste as inputs, illustrating how local contexts drive innovation in sustainability.

Case studies reveal that outcomes of circular business model implementation vary widely depending on systemic support. In developing countries, successful initiatives often rely on local entrepreneurship and incremental innovation, though they face obstacles such as limited access to capital and inadequate policy support (Hossain & Sahajwalla, 2024). Conversely, in advanced economies, regulatory environments and consumer awareness tend to drive adoption, but challenges persist in market acceptance and compliance costs (Gottardo et al., 2021). For instance, Dhayal et al. (2025) show how circular economy initiatives in developing nations often succeed where there is alignment between community engagement and business strategies, but falter when technological or financial resources are lacking. These findings underscore that sustainable business model innovation cannot be divorced from its socio-economic and policy context.

In comparative perspective, European and Nordic economies illustrate advanced adoption of circular business models due to supportive policy environments, including incentives for recycling and renewable energy integration (Khan et al., 2021; Stefanis et al., 2024). By contrast, Asian economies such as China and India demonstrate rapid but uneven progress, with strong emphasis on digitalization of supply chains but weaker infrastructure for recycling and waste recovery (Yu et al., 2024; Lim et al., 2024). These differences reveal that while the principles of circular economy are globally recognized, their practical application is deeply shaped by regional policy frameworks, industrial capacity, and consumer behavior.

Summary of Findings

Across all thematic areas, the literature points to clear evidence that integrating green technologies into circular economy frameworks delivers tangible environmental and economic benefits. Product design informed by lifecycle analysis ensures reduced environmental impacts, renewable energy technologies advance decarbonization despite storage challenges, biomaterials like lignin offer promising alternatives to fossil-based resources, and sustainable business models embed circularity into industrial practices. However, the results also expose persistent barriers, including technological constraints, insufficient policy alignment, and systemic inequalities between developed and developing regions.

These findings underscore the importance of multi-level strategies that combine technological innovation, regulatory support, and organizational adaptation. Moreover, the global comparison highlights the uneven progress across countries, suggesting that while circular economy practices are advancing, their full potential will only be realized through greater harmonization of policies, improved technological infrastructures, and sustained investments in innovation.

The integration of green technologies within circular economy frameworks aligns closely with global policy trajectories that seek to foster sustainability transitions across multiple industrial sectors. A significant body of literature demonstrates that effective implementation of green innovations requires synergy between technological adoption and policy frameworks that incentivize sustainable practices. For instance, Khan et al. (2021) document how Nordic countries have successfully utilized policy interventions to accelerate green innovation, demonstrating the importance of aligning regulatory incentives with technological uptake. These cases reveal how government support in the form of subsidies, tax breaks, and capacity-building programs creates enabling environments for circular business models to thrive. Rahman et al. (2025) further emphasize that green technology transmission represents a critical pathway toward achieving international sustainability commitments, particularly those outlined in the Sustainable Development Goals (SDGs). This body of evidence highlights how consistency between global policy ambitions and national-level implementation plays a decisive role in shaping technological transitions.

Systemic barriers, however, remain a central obstacle to widespread adoption. Economic constraints represent one of the most cited inhibitors, especially for small and medium-sized enterprises (SMEs) that lack the capital to invest in advanced technologies. While large corporations in Europe and Asia have benefited from both state subsidies and international financing mechanisms, smaller firms often remain excluded from these opportunities, creating uneven progress in sustainable transitions (Losada et al., 2019). Social barriers add another layer of complexity. Dzwigo et al. (2021) argue that the lack of stakeholder awareness and education regarding the benefits of circular practices reduces adoption rates. Without targeted education programs and accessible knowledge-sharing platforms, many industries continue to operate within traditional linear models, even when greener alternatives exist.

Policy uncertainty compounds these economic and social barriers. Studies consistently show that fragmented or inconsistent regulatory frameworks discourage long-term investment in green technologies (Liu et al., 2024). Businesses often face difficulties in aligning strategies with shifting government priorities, particularly in countries where sustainability policies are not harmonized across regions or sectors. This unpredictability undermines confidence in sustainable investments and slows the pace of transition. The importance of coherent policy frameworks is underscored by international experiences in renewable energy deployment, where strong and stable regulations have proven instrumental in driving large-scale adoption.

The interplay of these systemic barriers reveals how deeply structural factors shape sustainability outcomes. High upfront costs and uncertain returns on investment limit industrial willingness to engage in radical innovation. This is particularly evident in the case of photovoltaics, where despite advances in efficiency, adoption in developing economies lags due to financial and infrastructural deficits (Pardal et al., 2020; Coelho et al., 2020). Similarly, the promise of biomaterials such as lignin remains underexploited due to technical barriers in extraction and scaling, challenges that are exacerbated by the absence of coordinated policy and industrial support (Pagnotta, 2025; Sahu et al., 2024). These systemic obstacles highlight the need for multidimensional strategies that simultaneously address technological, financial, and governance challenges.

Proposed solutions in the literature emphasize the integration of digital platforms, financial incentives, and institutional partnerships to overcome these barriers. Liu et al. (2024) suggest that coupling digital technologies with circular practices offers new opportunities for efficiency and transparency. Digital platforms can enable real-time monitoring of resource flows, improving traceability and accountability across supply chains. By linking these tools to policy-driven incentives, industries may be encouraged to invest more confidently in sustainable technologies. Rahman et al. (2025) expand on this argument by advocating for green financing instruments, such as low-interest loans and tax incentives, that reduce financial risks associated with adopting low-carbon technologies. Such instruments have already proven successful in renewable energy projects, where financial barriers were mitigated through state-backed guarantees and international climate funds.

Public–private partnerships represent another recurring recommendation. Chutipat et al. (2023) argue that robust collaboration between governments, private enterprises, and research institutions is critical to accelerating green technology adoption. These partnerships not only pool resources for research and development but also create channels for knowledge exchange and capacity building. Particularly for SMEs, which often lack access to technological expertise and funding, public–private cooperation can bridge critical gaps. Evidence from construction industries in developing countries shows that partnerships supported by local governments have enabled circular practices in waste management, even in contexts of limited resources (Gyimah et al., 2025). Such models indicate the scalability of cooperative frameworks when adapted to specific regional conditions.

While these solutions present pathways forward, limitations in existing research must also be acknowledged. Many studies rely on case-specific analyses that, while insightful, limit the generalizability of findings across different sectors and geographies. For example, the success of policy-driven incentives in Nordic countries may not translate directly to developing economies with weaker institutional capacities (Khan et al., 2021). Similarly, studies on lignin valorization often focus on experimental laboratory settings, which may not fully reflect the practical challenges of scaling technologies to industrial levels (Ligarda-Samanez et al., 2025). This gap underscores the importance of expanding research to include longitudinal and cross-sectoral analyses that can provide more comprehensive insights into systemic drivers and barriers.

Another limitation is the uneven representation of geographical regions in the literature. While Europe and Asia dominate discussions of circular economy and green innovation, Africa and Latin America remain underexplored in empirical research. This lack of representation restricts understanding of how contextual factors, such as informal economies or differing policy environments, shape the adoption of green technologies. Expanding research to encompass these regions would not only diversify the evidence base but also strengthen the global applicability of sustainability frameworks.

Future research should also address methodological limitations. Many existing studies employ qualitative approaches, such as case studies and interviews, which, while rich in detail, may not provide sufficient statistical robustness to inform policy at scale. Greater reliance on mixed-methods research and quantitative modeling could provide stronger evidence for the systemic impacts of circular practices. Furthermore, the development of standardized indicators for assessing sustainability outcomes remains a pressing need (Vinay et al., 2025). Without harmonized metrics, it is difficult to evaluate the effectiveness of policies or compare outcomes across regions, limiting the capacity of decision-makers to design evidence-based strategies.

Finally, the literature indicates the importance of fostering an interdisciplinary research agenda that bridges engineering, economics, and social sciences. The challenges of integrating green technologies into circular systems cannot be addressed through technological innovation alone; they require understanding of social behaviors, economic incentives, and governance structures. Collaborative research that integrates these perspectives could generate more holistic solutions, addressing not only technical barriers but also the systemic conditions that shape adoption. By aligning interdisciplinary inquiry with global policy priorities, future studies can enhance both the academic and practical contributions of circular economy scholarship.

CONCLUSION

This narrative review highlights the critical role of integrating green technologies within circular economy frameworks to advance sustainable innovation across industries. The findings emphasize that product design informed by lifecycle assessment, advancements in photovoltaic technologies, valorization of lignin-based biomaterials, and sustainable business models collectively contribute to reducing environmental impacts and fostering long-term resilience. However, systemic barriers, including high initial costs, technical limitations, policy fragmentation, and uneven global capacities, continue to hinder widespread adoption. These challenges underscore the urgency of coordinated interventions that align technological innovation with supportive governance structures. Policy measures such as harmonized regulations, fiscal incentives, and stronger public–private partnerships can provide enabling conditions for businesses, particularly small and medium-sized enterprises, to adopt circular practices. Future research should address methodological gaps by developing standardized indicators, expanding quantitative analyses, and incorporating perspectives from underrepresented regions to ensure broader applicability of findings. Advancing interdisciplinary inquiry that bridges technological, economic, and social dimensions will be essential to overcoming systemic obstacles. Strengthening product design strategies, renewable energy integration, biomaterial innovation, and circular business models remains central to building sustainable economies capable of responding effectively to global environmental challenges.

REFERENCE

Agarwal, S., Kumar, N., Tyagi, M., & Garg, R. (2025). Integrating soft computing techniques for optimizing green vehicular communications and networking in circular digital supply chain. *Journal of Science and Technology Policy Management.* https://doi.org/10.1108/jstpm-03-2024-0112

Alaghemandi, M. (2025). Sustainable innovation management: balancing economic growth and environmental responsibility. *Sustainability, 17*(10), 4362. https://doi.org/10.3390/su17104362

Benjaafar, H., Berrichi, A., Jai, F., & Arabi, M. (2025). New generation agricultural cooperatives: towards a sustainable model serving ecology and environmental preservation. *E3S Web of Conferences, 632,* 03001. https://doi.org/10.1051/e3sconf/202563203001

Biber-Freudenberger, L., Ergeneman, C., Förster, J., Dietz, T., & Börner, J. (2020). Bioeconomy futures: expectation patterns of scientists and practitioners on the sustainability of bio-based transformation. *Sustainable Development, 28*(5), 1220-1235. https://doi.org/10.1002/sd.2072

Borysiak, O., & Brych, V. (2022). Post-covid-19 revitalisation and prospects for climate neutral energy security technologies. *Problemy Ekorozwoju, 17*(2), 31-38. https://doi.org/10.35784/pe.2022.2.04

Chutipat, V., Sonsuphap, R., & Pintong, W. (2023). Bio-circular-green model in a developing economy. *Corporate Governance and Organizational Behavior Review, 7*(1), 150-157. https://doi.org/10.22495/cgobrv7i1p14

Coelho, M., Pereira, R., Rodrigues, A., Teixeira, J., & Pintado, M. (2020). The use of emergent technologies to extract added value compounds from grape by-products. *Trends in Food Science & Technology, 106,* 182-197. https://doi.org/10.1016/j.tifs.2020.09.028

Corcione, F. (2024). Green mobility and the environment: a dialogue among researchers. https://doi.org/10.4271/9781468608021

Dhayal, K., Giri, A., Agrawal, R., Agrawal, S., Samadhiya, A., & Kumar, A. (2025). Do the innovative technological advancements foster the green transition pathways for industry 5.0? A perspective toward carbon neutrality. *Benchmarking: An International Journal.* https://doi.org/10.1108/bij-04-2024-0330

Dzwigo, H., Трушкіна, Н., & Kwiliński, A. (2021). The organizational and economic mechanism of implementing the concept of green logistics. *Virtual Economics, 4*(2), 41-75. https://doi.org/10.34021/ve.2021.04.02(3)

Gottardo, S., Mech, A., Drbohlavová, J., Małyska, A., Bøwadt, S., Sintes, J., … & Rauscher, H. (2021). Towards safe and sustainable innovation in nanotechnology: state-of-play for smart nanomaterials. *NanoImpact, 21,* 100297. https://doi.org/10.1016/j.impact.2021.100297

Gupta, P. (2025). Digital transformation as a catalyst for sustainability for advancing circular economy and environmental innovation (pp. 117-150). https://doi.org/10.4018/979-8-3693-9909-5.ch005

Hong, Z., & Xiao, K. (2024). Digital economy structuring for sustainable development: the role of blockchain and artificial intelligence in improving supply chain and reducing negative environmental impacts. *Scientific Reports, 14*(1). https://doi.org/10.1038/s41598-024-53760-3

Hossain, R., & Sahajwalla, V. (2024). Current recycling innovations to utilize e-waste in sustainable green metal manufacturing. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 382*(2284). https://doi.org/10.1098/rsta.2023.0239

Khan, J., Johansson, B., & Hildingsson, R. (2021). Strategies for greening the economy in three Nordic countries. *Environmental Policy and Governance, 31*(6), 592-604. https://doi.org/10.1002/eet.1967

Ligarda-Samanez, C., Huamán-Carrión, M., Ponce, W., Cruz, G., Huamaní, D., Cabel-Moscoso, D., … & Jilaja-Carita, E. (2025). Technological innovations and circular economy in the valorization of agri-food by-products: advances, challenges and perspectives. *Foods, 14*(11), 1950. https://doi.org/10.3390/foods14111950

Lim, S., Jamaludin, A., Islam, A., Weerabahu, S., & Priyono, A. (2024). Unlocking potential for a circular bioeconomy transition through digital innovation, lean manufacturing and green practices: a review. *Management of Environmental Quality: An International Journal.* https://doi.org/10.1108/meq-11-2023-0386

Loreño, D., & Yu, H. (2025). Strategies for sustainable development leveraging MSMEs in the Philippine blue and green economy (pp. 299-330). https://doi.org/10.4018/979-8-3693-7893-9.ch012

Losada, R., Gómez-Ramos, A., & González, M. (2019). Rural areas receptivity to innovative and sustainable agrifood processes: A case study in a viticultural territory of central Spain. *Regional Science Policy & Practice, 11*(2), 307-328. https://doi.org/10.1111/rsp3.12187

Liu, Z., Liu, Y., & Osmani, M. (2024). Integration of smart cities and building information modeling (BIM) for a sustainability-oriented business model to address sustainable development goals. *Buildings, 14*(5), 1458. https://doi.org/10.3390/buildings14051458

Luu, T., Das, B., Biswal, S., Yadav, M., & Chandel, A. (2024). Sustainability and knowledge management in entrepreneurial supply chains (pp. 261-290). https://doi.org/10.4018/979-8-3693-3386-0.ch010

Megawati, S., Herdiansyah, H., Machmud, A., Antriyandarti, E., & Sudirman, S. (2024). Integrating circular economy, digital economy, and social protection policies to drive green business innovation: insights from Indonesia's culinary SMEs. *Problems and Perspectives in Management, 22*(4), 368-381. https://doi.org/10.21511/ppm.22(4).2024.28

Mokdad, Z. (2025). The role of business innovation in transforming social systems for sustainability (pp. 533-548). https://doi.org/10.4018/979-8-3373-1280-4.ch018

Motaleb, K., Pranta, A., Karim, F., Islam, M., Islam, M., & Janutėnienė, J. (2025). Bio-waste as a resource for sustainable nanocomposites: strategies and multifunctional applications. *Functional Composites and Structures, 7*(2), 022002. https://doi.org/10.1088/2631-6331/add9e0

Nasim, B., Venschott, M., & Magnus, C. (2024). Greening the future through digital transformation (pp. 278-307). https://doi.org/10.4018/979-8-3693-2845-3.ch015

Nygaard, A. (2022). The geopolitical risk and strategic uncertainty of green growth after the Ukraine invasion: how the circular economy can decrease the market power of and resource dependency on critical minerals. *Circular Economy and Sustainability, 3*(2), 1099-1126. https://doi.org/10.1007/s43615-022-00181-x

O'Connor, M., Zimmerman, J., Anastas, P., & Plata, D. (2016). A strategy for material supply chain sustainability: enabling a circular economy in the electronics industry through green engineering. *ACS Sustainable Chemistry & Engineering, 4*(11), 5879-5888. https://doi.org/10.1021/acssuschemeng.6b01954

Pagnotta, L. (2025). Sustainable netting materials for marine and agricultural applications: a perspective on polymeric and composite developments. *Polymers, 17*(11), 1454. https://doi.org/10.3390/polym17111454

Pant, P., & Gandhi, D. (2025). The economics of sustainability (pp. 427-452). https://doi.org/10.4018/979-8-3373-0608-7.ch019

Pardal, A., Romeira, T., & Durão, A. (2020). Eco green campus: challenges and opportunities. The study case of Polytechnic Institute of Beja. *E3S Web of Conferences, 171,* 01010. https://doi.org/10.1051/e3sconf/202017101010

Purwanto, E., Iskandar, Y., Mala, C., Dewi, C., & Windarko, W. (2025). Circular economy and sustainable manufacturing: a bibliometric analysis. *IOP Conference Series: Earth and Environmental Science, 1441*(1), 012021. https://doi.org/10.1088/1755-1315/1441/1/012021

Rahman, S., Ahsan, A., & Sharma, R. (2025). Impact of green technology transmission on sustainable development. *Sustainability, 17*(5), 1981. https://doi.org/10.3390/su17051981

Raman, R., Sreenivasan, A., Suresh, M., Patwardhan, A., & Nedungadi, P. (2023). Green supply chain management research trends and linkages to UN Sustainable Development Goals. *Sustainability, 15*(22), 15848. https://doi.org/10.3390/su152215848

Reema, R., Khanikar, R., Bailung, H., & Sankaranarayanan, K. (2022). Review of the cold atmospheric plasma technology application in food, disinfection, and textiles: a way forward for achieving circular economy. *Frontiers in Physics, 10.* https://doi.org/10.3389/fphy.2022.942952

Romani, A., Pinelli, P., Ieri, F., & Bernini, R. (2016). Sustainability, innovation, and green chemistry in the production and valorization of phenolic extracts from *Olea europaea L. Sustainability, 8*(10), 1002. https://doi.org/10.3390/su8101002

Sahu, P., Thorbole, A., & Gupta, R. (2024). Polyesters using bioderived furandicarboxylic acid: recent advancement and challenges toward green PET. *ACS Sustainable Chemistry & Engineering, 12*(18), 6811-6826. https://doi.org/10.1021/acssuschemeng.4c01123

Singh, R. (2025). Integrating Industry 4.0, circular economy, and green HRM: a framework for sustainable transformation. *Sustainability, 17*(7), 3082. https://doi.org/10.3390/su17073082

Singh, R., & Thanki, H. (2024). Greening the supply chain: institutional pressures, data-driven innovations, and the road to circular sustainability. *Business Strategy and the Environment, 33*(6), 6029-6044. https://doi.org/10.1002/bse.3788

Stefanis, C., Stavropoulos, A., Stavropoulou, E., Tsigalou, C., Constantinidis, T., & Bezirtzoglou, E. (2024). A spotlight on environmental sustainability in view of the European Green Deal. *Sustainability, 16*(11), 4654. https://doi.org/10.3390/su16114654

Thormann, L., Neuling, U., & Kaltschmitt, M. (2021). Opportunities and challenges of the European Green Deal for the chemical industry: an approach measuring innovations in bioeconomy. *Resources, 10*(9), 91. https://doi.org/10.3390/resources10090091

Vinay, B., Nikodimos, Y., Agnihotri, T., Ahmed, S., Hagos, T., Hasan, R., … & Hwang, B. (2025). Fluorine-free electrolytes in batteries: principles, strategies, and advances. *Energy & Environmental Science.* https://doi.org/10.1039/d4ee04820b

Xiao, J., Chen, S., Tan, Z., Chen, Y., Wang, J., & Han, J. (2024). Examining the carbon reduction effect of renewable resource utilization: based on national "urban mining" demonstration base. *Industrial Management & Data Systems, 124*(12), 3298-3323. https://doi.org/10.1108/imds-10-2023-0747

Yin, C., Cui, Y., & Liu, Y. (2022). Effect and mechanism of economic circulation in the middle and lower reaches of the Yellow River: multiregional input–output model and industrial complex network approaches. *Sustainability, 14*(19), 12922. https://doi.org/10.3390/su141912922

Yu, P., Zhang, Z., Wong, S., Lu, S., Chen, Y., & Wang, Y. (2024). The role of technologies in facilitating circular economy of China's e-commerce sector (pp. 151-174). https://doi.org/10.4018/979-8-3693-6392-8.ch008