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Current Trends on Innovability and Sustainable Innovation

Edited by

Anna Ujwary-Gil
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Introduction to the Innovability Index: Beyond the fusion of innovation and sustainability

***Anna Ujwary-Gil*[1], *Anna Florek-Paszkowska*[2]**

Abstract

The integration of innovation and sustainability, conceptualized as innovability, represents a strategic construct for addressing global challenges such as climate change, resource constraints, and social inequality. The conceptual understanding of innovability has advanced, but its empirical measurement and operationalization remain underdeveloped. This conceptual paper introduces the Innovability Index, designed to evaluate the extent to which countries, regions, or organizations embed sustainability principles. The index encompasses four dimensions: technological innovation for sustainability, environmental sustainability, social inclusiveness, and sustainable business practices. Each dimension is assessed through a set of indicators normalized, weighted, and aggregated to generate a composite performance score. The Innovability Index provides a structured approach for benchmarking sustainable innovation capabilities. It is a practical tool for policymakers, firms, and researchers to align innovation ecosystems with sustainability imperatives and the Sustainable Development Goals (SDGs). This conceptual paper opens the thematic issue of innovability and sustainable innovation, as well as addresses a gap in the literature by introducing the initial attempt to measure innovability.

Keywords: *Innovability, Innovability Index, sustainable development, ESG, sustainability, sustainable innovation, technological innovation, environmental sustainability, social inclusiveness, sustainable business practices,*

INTRODUCTION

The intersection of innovation and sustainability has emerged as a focal point in contemporary research, reflecting the growing recognition that long-term economic growth must be balanced with environmental stewardship and social equity (e.g., Xetor & Mensah, 2025). Innovation, often framed as the engine of economic progress, has traditionally been studied in isolation from sustainability focused on preserving resources and ensuring equity development. However, the increasing urgency of global challenges, such as climate change, resource depletion, and social inequality, necessitates an integrated approach that aligns innovation with sustainability objectives.

The concept of innovability, which synthesizes innovation and sustainability, builds on this imperative by emphasizing the creation of innovative solutions that drive economic value while addressing environmental and societal needs. Despite its conceptual richness, the operationalization and measurement of innovability remain underexplored. Existing frameworks, such as the Global Innovation Index (GII) (Huang et al., 2024; Nasir & Zhang, 2024) and the Sustainable Development Goals Index (SDG Index) (Anselmi et al., 2024), partially address these domains, however without showing

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their convergence. The GII, for instance, evaluates countries' innovation capabilities and outputs but does not explicitly focus on environmental and social dimensions. Conversely, the SDG Index emphasizes sustainability outcomes but does not systematically assess the role of innovation in achieving these goals.

Several studies have sought to integrate elements of innovation and sustainability. Research on sustainability-oriented innovation (SOI) (Fiandrino et al., 2025) highlights how firms develop environmentally and socially responsible products and processes. Similarly, investigations into green innovation (Zhan et al., 2025) mainly focus on technological advancements that mitigate environmental impact. These studies often prioritize the innovation process or sustainability outcomes, neglecting the holistic interplay between the two.

Our initial research addresses a literature gap by proposing and evaluating the Innovability Index, a composite measure that can quantify the capacity of countries, regions, or organizations to innovate sustainably. Unlike prior frameworks, the Innovability Index integrates technological, environmental, social, and business dimensions, comprehensively assessing how innovation and sustainability interact. By doing so, we offer a tool for benchmarking performance, guiding policy, and fostering cross-sectoral collaboration. Thus, the primary research question (RQ) is as follows:

RQ: How can the Innovability Index be utilized to evaluate and enhance the sustainable innovation performance of countries, regions, or organizations?

This question aims to explore not only the measurement of innovability but also its implications for policy and strategy. Thus, our conceptual considerations seek to provide an understanding of how entities can leverage the Innovability Index to identify strengths, address weaknesses, and align their innovation ecosystems with sustainability goals. This approach contributes to the broader discourse on sustainable development and aligns innovation with ecological and societal imperatives.

Our conceptual paper was developed as part of the outcomes of the 22nd International Conference on Economics, Finance, and Management (ICEFM 2024), held on May 30–31, 2024, in Lima, Peru. The conference, organized under the patronage of the Embassy of Poland in Lima and the Embassy of Peru in Warsaw, was dedicated to the theme "Balancing Contemporary Challenges With Innovability." This thematic issue on current innovability and sustainable innovation trends includes six articles in the Contributors section.

LITERATURE BACKGROUND

The term "innovability," a conceptual fusion of innovation and sustainability, was initially introduced by Mi Dahlgaard-Park and Dahlgaard (2010), who defined innovability as an organizational capability that enhances innovation and learnability to support continuous improvement. This framing positioned innovability within the discourse of total quality management and emphasized its role in fostering long-term adaptability and organizational learning. Building upon this foundation, Dervitsiotis (2010) expanded the concept by explicitly integrating sustainability considerations into innovability. He articulated innovability as a strategic capability that brings into line continuous innovation with sustainability principles to ensure competitiveness while responding to broader ecological and societal challenges.

In the corporate sector, Enel, a leading multinational energy company, operationalized innovability through its "Open Innovability" strategy, combining open innovation platforms with sustainability objectives. Under its leadership, Enel institutionalized innovability through the creation of dedicated innovation hubs and multi-sectoral collaborations aimed at co-developing solutions aligned with the United Nations Sustainable Development Goals (Monteiro & Garcia, 2019; Visnjic & Malizou, 2022). These efforts translated the abstract concept of innovability into governance and implementation, illustrating its potential to drive organizational strategic transformation (Lippolis et al., 2023).

In academia, De la Vega Hernández and Barcellos de Paula (2021) conducted a bibliometric analysis of literature from 1990 to 2018, mapping the convergence of innovation and sustainability. They identified a sustained increase in scholarly output linking these domains and proposed *innovability* as a management strategy defined by "innovation capability in a sustainable way." Their study positioned innovability as a theoretically grounded and practically oriented construct, underlying its potential for innovation systems with sustainability imperatives.

Innovability can be investigated at the intersection of innovation management theories and sustainability science. From the innovation side, it is rooted in the dynamic capabilities perspective (Teece et al., 1997), which posits that organizations must continuously reconfigure resources to remain competitive in evolving environments. From the

sustainability perspective, it resonates with the triple bottom line approach, which advocates balancing economic, environmental, and social performance to achieve long-term viability and corporate responsibility (Elkington, 1997). Innovability also aligns with organizational ambidexterity, as detailed by O'Reilly and Tushman (2008), underscoring the necessity of balancing explorative innovation (developing novel opportunities) with exploitative refinement of sustainable practices (optimizing existing processes) to simultaneously advance innovation and sustainability goals. This dual focus means that innovation efforts are inherently sustainable, just as sustainability initiatives are inherently innovative – an inseparability that characterizes innovability's strategic orientation.

Innovability shares conceptual terrain with sustainability-oriented innovation (SOI) and green innovation (GI). On one hand, SOI typically refers to innovation activities explicitly addressing sustainability goals, often through targeted product, process, or business model innovations (Adams et al., 2016; Fiandrino et al., 2025). On the other hand, GI focuses on minimizing environmental harm and frequently treats sustainability as a functional add-on to traditional innovation processes, treating it not as an outcome but as an intrinsic design principle (Ibarra-Cisneros et al., 2024; Zhan et al., 2025).

Building upon the existing literature, innovability can be delineated into four interrelated dimensions: 1) Technological Innovation for Sustainability, 2) Environmental Sustainability, 3) Social Inclusiveness, and 3) Sustainable Business Practices.

1) Technological innovation for sustainability: This dimension reflects the extent to which technological advancements are strategically directed toward sustainable development (Secundo et al., 2020). Recent research has demonstrated that eco-innovation (Chien et al., 2023; Triguero et al., 2022), including clean technologies (Xie et al., 2024), energy efficiency systems (Olabi et al., 2023), and digital tools for sustainability (Javeed et al., 2025), can deliver both economic and environmental benefits. Empirical studies confirm that targeted R&D investment and technological output in sectors such as renewable energy, waste reduction, and circular economy models serve as key indicators of an economy's or organization's commitment to sustainability-oriented innovation (Montresor & and Vezzani, 2023).
2) Environmental sustainability: This dimension addresses the ecological outcomes of innovation and emphasizes the importance of minimizing environmental degradation through innovation strategies. Empirical evidence from firm-level studies demonstrates that organizations adopting carbon reduction initiatives, life-cycle assessment practices, and circular business models improve environmental performance and achieve regulatory compliance and operational efficiency (Saba et al., 2023; Sharma et al., 2021; Singh et al., 2020). These findings support the integration of environmental performance metrics as a core component of sustainable innovation evaluation.
3) Social Inclusiveness: This dimension evaluates how innovation practices promote equity and inclusion. The social dimension is recognized as essential for ensuring broad access to innovation's benefits. The integration of social factors into economic decisions is increasingly seen as essential for long-term stability, as societies marked by inequality are more prone to unrest and instability (Mdingi & Ho, 2021). Studies show that initiatives involving marginalized stakeholders, such as community-based co-creation and inclusive technology diffusion, contribute to social cohesion and innovation effectiveness, particularly in emerging markets (De Tommaso & Pinsky, 2022).
4) Sustainable Business Practices: This dimension examines how sustainability principles are embedded within business operations and governance structures. Corporate sustainability extends CSR by focusing on long-term value creation through sustainable business practices. Firms adopt sustainability strategies by improving resource efficiency (Sun et al., 2023), reducing carbon footprints (Carvalho et al., 2016), embracing renewable energy (Zhang & Kong, 2022), and adopting circular economy principles (Arshi & Wallis, 2024; Stewart & Niero, 2018). Practices such as sustainable supply chain management (Alam et al., 2025; Jabber et al., 2024) and ESG reporting have been associated with sustainable business practices (Mohamed Riyath & Inun Jariya, 2024; Yadav et al., 2024).

Despite these conceptual advancements, no universally accepted framework exists to comprehensively and quantitatively measure innovability. Some companies like Enel have developed internal frameworks and proprietary indicators to evaluate innovability. These remain context-specific and are not openly accessible for scholarly validation (Monteiro & Garcia, 2019). Existing empirical studies, such as the Suzano case (De Tommaso & Pinsky, 2022), is limited in its sectoral applicability and does not provide a generalizable quantitative assessment. The need for a validated, scalable measurement instrument that encompasses the multidimensional nature of innovability remains pressing. The Innovability Index introduced in this paper addresses this gap by presenting the four aforementioned dimensions to assess and enhance innovability across diverse settings.

INTRODUCING THE INNOVABILITY INDEX

The Innovability Index is a proposed composite measure designed to evaluate the ability of countries, regions, or organizations to simultaneously foster innovation and sustainability. The concept of innovability, as presented above, emphasizes the development of new technologies, processes, and business models that generate economic, social, and environmental value. The Innovability Index aims to comprehensively assess how well entities integrate sustainability into their innovation ecosystems, ensuring that innovation does not come at the expense of environmental degradation or social inequity. This index seems promising for policymakers, corporations, and researchers seeking to measure progress in achieving sustainable innovation.

The Innovability Index is grounded in two main theoretical pillars: innovation theory and sustainability science. As noted, innovation theory highlights the role of technological change and entrepreneurship in economic growth and industrial transformation, while sustainability science emphasizes long-term environmental health, social equity, and resource preservation. By merging these two disciplines, the Innovability Index seeks to quantify how well an economy or organization innovates in ways that support sustainable development goals (SDGs). The index integrates multiple dimensions into a composite score. These dimensions are selected based on their relevance to the twin objectives of promoting innovation and ensuring sustainability. The index uses a set of key indicators to measure each dimension, enabling cross-country or cross-organizational comparisons of innovability performance.

We propose that the Innovability Index comprises four main dimensions listed above, each capturing a critical aspect of innovability. They include: 1) Technological Innovation for Sustainability, 2) Environmental Sustainability, 3) Social Inclusiveness, and 4) Sustainable Business Practices (Table 1). Technological Innovation for Sustainability assesses how economies or organizations can develop and adopt technologies that contribute to sustainability. It focuses on the generation of new products, processes, or services that minimize environmental impacts, enhance resource efficiency, or promote the transition to a green economy. Environmental Sustainability evaluates the environmental outcomes of innovation and assesses whether technological advancements are being leveraged to reduce environmental degradation and promote the sustainable use of resources. It emphasizes the extent to which innovation contributes to improving environmental health and reducing ecological footprints. Social Inclusiveness focuses on the social impact of innovation, ensuring that technological advancements reduce inequality and promote social inclusion. Social inclusiveness in innovability is critical for ensuring that innovation benefits are distributed equitably and disadvantaged groups are not excluded from participating in and benefiting from innovative activities. Finally, the Sustainable Business Practices dimension assesses how businesses and industries adopt sustainable practices and embed sustainability into their innovation strategies. It measures how firms are transitioning towards sustainable business models and the degree to which they are responsible for their environmental and social impacts.

Table 1. The Innovability Index dimensions and indicators

Dimensions	Key indicators	Definition
1. Technological Innovation for Sustainability	R&D expenditure on green technologies	The percentage of total research and development (R&D) expenditure devoted to environmentally friendly technologies (e.g., renewable energy, energy efficiency, waste reduction).
	Number of clean technology patents	A measure of the inventive output in the clean technology sector, including renewable energy, pollution control, and sustainable agriculture.
	Innovation output in sustainable sectors	A measure of the share of innovation outputs (products, processes, services) in sectors that contribute to sustainability, such as renewable energy, water management, and sustainable construction.
2. Environmental Sustainability	Carbon intensity of innovation	Greenhouse gas emissions per unit of innovative output (e.g., per patent or per R&D expenditure).
	Resource efficiency	The ratio of economic output (e.g., GDP) to resource input (e.g., energy, water, and material use), measuring the extent to which innovation enhances resource efficiency.
	Reduction in environmental externalities	A composite indicator measuring reductions in pollution, waste, and ecosystem degradation due to innovation efforts.

Dimensions	Key indicators	Definition
3. Social Inclusiveness	Access to innovative technologies	The percentage of the population with access to sustainable innovations (e.g., renewable energy, clean water technologies, and digital tools for social inclusion).
	Employment in sustainable sectors	The share of total employment in industries or sectors focused on sustainability and low-carbon economic activities.
	Social impact of innovation	A measure of how innovations address social challenges, such as poverty reduction, gender equality, and access to education or healthcare, in line with the Sustainable Development Goals (SDGs).
4. Sustainable Business Practices	Sustainable supply chain integration	The percentage of businesses that have integrated sustainability into their supply chains, ensuring that suppliers adhere to environmental and social standards.
	Circular economy adoption	The extent to which businesses adopt circular economy principles, such as recycling, reuse, and waste minimization, in their operations.
	Corporate sustainability reporting	The percentage of companies publicly report their sustainability performance and have adopted ESG (Environmental, Social, and Governance) standards.

Each dimension is measured through its respective indicators, which are the normalization of raw data, calculation of dimension scores, and aggregation into the final composite index. The following steps outline the calculation method for the Innovability Index:

Step 1) Normalization of indicators

To ensure comparability across indicators with different units and scales, each indicator is normalized on a common scale, typically ranging from 0 to 100. The normalization method (Formula 1) commonly employed is min-max scaling, which transforms the raw indicator values into a dimensionless score. For each indicator X, the normalized value $X_{\text{normalized}}$ is calculated as:

$$X_{normalized} = \frac{X - X_{min}}{X_{max} - X_{min}} x\ 100 \quad (1)$$

Where: X is the raw value of the indicator for the country, organization, or region being evaluated; X_{min} is the minimum value of the indicator across all entities in the dataset; X_{max} is the maximum value of the indicator across all entities; and $X_{\text{normalized}}$ is the normalized score, rescaled between 0 and 100.

Step 2) Dimension scores

The Innovability Index consists of four main dimensions: Technological Innovation for Sustainability, Environmental Sustainability, Social Inclusiveness, and Sustainable Business Practices. Each dimension is measured by a set of indicators, and the score for each dimension is computed by aggregating the normalized indicator scores. The aggregation can be done using a weighted sum of the normalized indicators (Formula 2).

For each dimension d, the score $S_{dimension,i}$ is calculated as the weighted sum of its n_d normalized indicators:

$$S_{dimension,d} = \sum_{i=1}^{n_d} \omega_i \cdot X_{normalized,i} \quad (2)$$

Where: ω_i is the weight assigned to indicator i within dimension d; $X_{normalized,i}$ is the normalized value of indicator i; n_d is the number of indicators in dimension d; and $S_{dimension,d}$ is the overall score for dimension d.

Weights ω_i can be assigned equally if no particular priority is given to any indicator, or they can be customized based on expert judgment or empirical significance.

Step 3) Overall Innovability Index Score

The final Innovability Index score $S_{Innovability}$ is calculated by aggregating the scores from the four main dimensions. This aggregation is typically performed using a weighted sum of the dimension scores, where weights reflect the relative importance of each dimension (Formula 3):

$$S_{Innovability} = \omega_{Tech} \cdot S_{Innovability,Tech} + \omega_{Env} \cdot S_{Innovability,Env} + \omega_{Social} \cdot S_{Innovability,Social} + \omega_{Business} \cdot S_{Innovability,Business} \quad (3)$$

Where: $S_{Innovability,Tech}$ is the score for Technological Innovation for Sustainability; $S_{Innovability,Env}$ is the score for Environmental Sustainability; $S_{Innovability,Social}$ is the score for Social Inclusiveness; $S_{Innovability,Business}$ is the score for Sustainable Business Practices; $\omega_{Tech}, \omega_{Env}, \omega_{Social}, \omega_{Business}$ are the weights assigned to each dimension, reflecting their relative importance. These weights are typically chosen based on expert input or strategic priorities and should sum to 1: $\omega_{Tech} + \omega_{Env} + \omega_{Social} + \omega_{Business} = 1$. In some cases, these weights may be equally distributed (i.e., ω=0.25) if all dimensions are considered equally important.

The final Innovability Index score $S_{Innovability}$ is a number between 0 and 100, with 100 representing the optimal performance in terms of integrating innovation and sustainability. Higher scores indicate a stronger capacity to innovate sustainably, while lower scores suggest potential weaknesses in either innovation or sustainability practices, or both.

The Innovability Index assesses the ability of economies, organizations, or regions to innovate in ways that are environmentally sustainable and socially inclusive. The Index relies on normalized indicators, dimension score calculations, and weighted aggregation of these scores into a single composite measure. It is a data-driven tool for benchmarking and comparing "innovability" performance, guiding efforts to foster sustainable innovation in pursuit of long-term economic, social, and environmental goals. A higher Innovability Index score signifies a robust ability to generate innovations that contribute positively to sustainability objectives, whereas a lower score highlights gaps where innovation systems may not be fully aligned with sustainability imperatives. This index can thus inform policymakers in identifying areas where public intervention (such as R&D incentives for green tech or support for inclusive innovation programs) is needed. It can likewise help business leaders and investors benchmark corporate performance in innovability, drive investment towards high-innovability ventures, and develop strategies for integrating sustainability more deeply into innovation processes. For researchers and academics, the index offers a novel metric for analyzing the relationship between innovation and sustainability across different contexts and for studying which factors most significantly contribute to higher innovability. Ultimately, the Innovability Index is proposed as a comprehensive, multidimensional measure of the capacity to innovate sustainably. By combining indicators of technological innovation, environmental sustainability, social inclusion, and responsible business practices, the index captures the complex interplay between innovation and sustainability. Importantly, the index enables cross-country, cross-sectoral, and organizational comparisons, thereby promoting accountability and encouraging the diffusion of sustainable innovations globally.

The Innovability Index is probably the first attempt to measure the intersection of innovation and sustainability. It provides a composite score that reflects how well an entity (such as a country, region, or organization) integrates sustainable practices into its innovation ecosystem. The index might track progress towards sustainable development goals (SDGs), foster a green economy, and promote socially inclusive innovation. However, like any composite index, the Innovability Index has strengths and limitations that warrant critical discussion.

On the strengths side, the Innovability Index's multi-dimensional structure, which combines Technological Innovation for Sustainability, Environmental Sustainability, Social Inclusiveness, and Sustainable Business Practices into a single score, captures the complexity and interdependence of innovation and sustainability. This multidimensional approach is essential because sustainable development requires balancing economic, environmental, and social priorities. By including diverse indicators across these domains, the index reflects a holistic view of sustainable innovation performance, which is critical for policy and strategic decision-making. Moreover, the index is designed to be adaptable to various contexts (national, regional, corporate), increasing its utility across sectors and geographic regions. The weighting of indicators and dimensions can be adjusted based on specific priorities or policy objectives, allowing for a tailored assessment of innovability in different settings. This flexibility is advantageous for policymakers and business leaders who may wish to emphasize certain aspects of sustainability or innovation according to their unique circumstances. The Innovability Index can also benchmark performance over time and identify areas where improvements are needed. Policymakers might leverage the index to design and implement interventions that enhance the sustainability of innovation systems. For example, if a country scores relatively low on the Environmental Sustainability dimension, governments could introduce

more substantial incentives for green technologies or stricter regulations on carbon emissions. Similarly, businesses can utilize the index to evaluate their progress toward corporate sustainability goals and enhance their innovation strategies (for instance, a low score in Social Inclusiveness might prompt a company to invest in more community-focused innovation programs or diversity initiatives in R&D teams).

One of the significant challenges in constructing and applying the Innovability Index is the availability and quality of data across all dimensions. Indicators such as clean technology patents or R&D expenditure on green technologies may be readily available for developed countries or large organizations, but harder to obtain for developing nations or smaller firms. Incomplete or inconsistent data can affect the reliability and comparability of the index, leading to biased assessments. The assignment of weights to different dimensions and indicators can be subjective, as it may depend on expert judgment or stakeholder priorities. Different stakeholders may value dimensions differently, for example, some may prioritize Technological Innovation for Sustainability, while others may emphasize Social Inclusiveness. This subjectivity can introduce variability in the index, potentially leading to debates about the validity of the overall score. On one hand, flexibility in weighting is a strength, on the other, it also complicates cross-country or cross-organizational comparisons, as different weighting schemes could yield different rankings.

As with any composite index, the Innovability Index entails an inherent risk of oversimplification. By aggregating multiple indicators into a single score, information about specific strengths and weaknesses within each dimension may be lost. For example, a high overall innovability score may mask poor performance in certain sub-indicators, such as resource efficiency or social inclusiveness. This simplification may lead to misinterpretations if users focus solely on the composite score without exploring into the underlying data. The assumption that innovation and sustainability are mutually reinforcing may not always hold true in practice. In some cases, there may be trade-offs between different index dimensions. Innovations that are environmentally sustainable may not be immediately profitable (Doś & Pattarin, 2024) or could require significant social adjustments, such as retraining workers from declining industries. Similarly, pursuing rapid technological innovation might lead to social inequality if access to new technologies is uneven. The Innovability Index may not fully capture such trade-offs, potentially giving a misleading impression of overall progress.

A real-world application of the index would demonstrate the utility but also reveal the practical challenges in accurately capturing the dynamic interplay between innovation and sustainability. The index must be applied carefully and interpreted in conjunction with qualitative methods to enhance its effectiveness and credibility. Future research should focus on pilot testing the Innovability Index across different contexts, refining the indicators and weighting schemes, statistical validation, as well as validating the index against external benchmarks (such as actual sustainability outcomes) to ensure its robustness. Through such continued refinement and validation, the Innovability Index can be developed into a rigorous tool that measures performance and stimulates improvement in the pursuit of sustainable innovation. Moreover, future research could revise this proposition through a much more advanced analysis of existing theories and methodologies, as well as innovation and sustainability indices, looking for possible synergies with an innovability index.

CONTRIBUTORS

The thematic issue "Current Trends on Innovability and Sustainable Innovation" assembles a collection of articles selected through a rigorous peer-review process that converge on the imperative of integrating innovation with sustainability, yet each contributes uniquely to the discourse through its empirical, conceptual, or methodological lens.

Portuguez-Castro et al. (2025) employ a systematic literature review to delineate leadership competencies essential for innovability within higher education institutions and the business sector. The authors identify five thematic competency clusters, including strategic vision, collaboration, commitment to sustainability, lifelong learning, and responsiveness to global megatrends. However, it also exposes the absence of standardized methodologies for measuring or implementing these competencies. The study's novelty resides in its explicit articulation of innovability leadership as a distinct paradigm and its call for educational institutions to bridge the competency gap for future sustainability-oriented leadership.

Najda-Janoszka et al. (2025) operationalize innovability through the integration of Science, Technology, and Innovation (STI) with Doing, Using, and Interacting (DUI) modes within a Living Lab framework. Through an in-depth case study on urban biodiversity management, they show that such integration enables co-created, context-sensitive innovations that balance ecological objectives with stakeholder needs. The methodological value of the study is found in its use of participatory action research; its conceptual contribution lies in extending innovability to encompass not just technological advancement but also socially inclusive and ecologically grounded practices.

Aqmala et al. (2025) empirically explore the mediating role of the Green Blue Ocean Strategy (GBOS) in enhancing frugal innovation via IoT and AI in resource-constrained entrepreneurial environments. Drawing on the resource-based view, the study reveals that IoT alone does not significantly affect frugal innovation, AI does, and GBOS serves as an effective strategic mediator. The originality of this study lies in the conceptualization and empirical validation of GBOS, a novel hybrid framework combining blue ocean strategy and green innovation, to foster sustainable competitiveness through digital technologies.

Kasztelan et al. (2025) quantify the relationship between eco-innovation, proxied by patent activity in recycling and secondary raw materials, and circular material use across EU countries. Utilizing panel data from 2010–2019, the study finds that higher eco-innovation intensity positively correlates with material circularity, although substantial intra-EU disparities persist. The value of this study lies in its methodological rigor and in addressing an empirical void regarding the material impacts of patent-driven eco-innovation on circular economy outcomes.

MacGregor Pelikánová et al. (2025), focused on the Unitary Patent System (UPS), investigates the correlation between innovation, economic resources, and patenting dynamics in the European Union. They demonstrate that the UPS fosters a unified legal framework for innovation protection, and its impact varies significantly across member states due to divergent levels of GDP per capita and gross domestic expenditure on R&D (GERD). The originality lies in its early empirical assessment of the UPS, revealing that economic capacity is a prerequisite but not a determinant of patenting efficiency, thus magnifying structural disparities within the EU innovation system.

Florek-Paszkowska and Ujwary-Gil (2025) introduce the Digital-Sustainability Ecosystem (DSE), a conceptual framework that elucidates the interplay between digital transformation and sustainable innovation. It systematizes five mechanisms: efficiency gains, dematerialization, circular economy enablement, innovation acceleration, and digital collaboration, and situates them within a multi-theoretical foundation encompassing resource-based, institutional, and stakeholder theories. The originality of this study lies in its holistic and adaptive framing, capturing dynamic feedback loops and systemic interdependencies. It is a theoretical contribution that sets the stage for empirical validation and practical implementation across diverse sectors.

All articles advance the frontier of innovability studies by revealing that sustainable innovation is not merely the outcome of technological progress, but a socio-technical construct requiring aligned governance, stakeholder engagement, and institutional reform.

CONCLUSION

The intention of this conceptual article was to initiate a discussion on the possibilities of measuring innovability through the proposed Innovability Index. Furthermore, to look at two complementary constructs such as innovation and sustainability, in a holistic way through the proposed index and its dimensions. The need to create such an Innovability Index emerged as a commentary voice of one of the authors of this article during the OPENING PANEL SESSION ON INNOVABILITY within the aforementioned ICEFM2024 project. We hope that this thematic issue, with all its valuable contributions referring to innovability and sustainable innovation, will gain the recognition of readers and become a part of the public and academic discourse in the light of existing solutions for measuring the effectiveness of innovation and sustainability.

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Anna Ujwary-Gil: Conceptualization, Methodology, Project Administration, Supervision, Writing Original Draft, Writing – Review & Editing. **Anna Florek-Paszkowska**: Conceptualization, Methodology, Project Administration, Supervision, Writing Original Draft, Writing – Review & Editing.

Conflicts of interest

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Leadership competencies for innovability: Bridging theory and practice for sustainable development

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Abstract

PURPOSE: *This study explores the critical leadership competencies necessary for fostering innovability— the integration of innovation and sustainability—within organizations, particularly inr education institutions (HEIs) and the business sector. The research seeks to address the gap in understanding how these competencies are developed in HEIs and whether they effectively prepare graduates with the skills needed for the current business context. Additionally, the study emphasizes the need to identify robust instruments for measuring these competencies to ensure their practical application in organizational settings.* ***METHODOLOGY:*** *A systematic literature review (SLR) was conducted using Scopus and Web of Science databases. The study employed a rigorous selection process to identify relevant empirical studies published between 2015 and 2024. A total of 53 articles were analyzed to address three key research questions related to the characteristics of innovability leadership, recommendations for developing immovability in organizations, and the methodologies or instruments used to identify these competencies. The analysis involved thematic synthesis and content analysis to extract insights and identify gaps in the existing literature.* ***FINDINGS:*** *The study identifies five key categories of leadership competencies essential for innovability, including strategic leadership, fostering a culture of collaboration, commitment to sustainability, continuous education, and sensitivity to global megatrends. Despite the recognition of these competencies, the study reveals a significant lack of empirical research on their practical implementation and measurement. The findings also highlight the need for robust tools to assess these competencies effectively. Additionally, the study provides several recommendations for developing innovability for their integration into the business sector, emphasizing the importance of leadership development programs, the integration of sustainability into corporate strategy, and the promotion of a collaborative organizational culture.* ***IMPLICATIONS:*** *Theoretically, the study contributes to the conceptual framework of innovability leadership by identifying critical competencies and suggesting a more integrated approach to leadership development in business education. Practically, the research underscores the importance of developing targeted training programs and assessment tools to cultivate these competencies in future leaders. This is particularly relevant for business schools, which play a crucial role in preparing students to address complex global challenges.* ***ORIGINALITY AND VALUE:*** *This study fills a gap in the literature by providing a detailed examination of the competencies required for innovability leadership and proposing directions for future research and practice. It offers a unique contribution by bridging the theoretical and practical aspects of innovability in leadership, particularly within the context of higher education.*

Keywords: *innovability, leadership competencies, sustainability, business education, systematic literature review, Sustainable Development Goals, SDGs, leadership development, educational innovation, higher education*

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INTRODUCTION

The contemporary world is becoming increasingly complex, and within this context, business sustainability has emerged as a critical element for addressing new challenges. Organizational leaders are progressively recognizing the need to adopt sustainable measures in hopes of generating a positive impact on society (Makower, 2021). This reality underscores the growing importance of integrating sustainability and innovation into the curricula of business schools within higher education institutions (Fang & O'Toole, 2023). Given the crucial role these schools play in training the future leaders of industry, it is essential that they impart the necessary knowledge and skills to their students to address complex societal issues and apply them within their organizations (Terán-Yépez et al., 2023). These educational programs must prepare the next generation of leaders to face uncertain challenges with knowledge, skills, attitudes, and values aligned with the Sustainable Development Goals (SDGs) and innovability (Portuguez-Castro & Castillo-Martínez, 2024). Despite the growing recognition of the importance of these approaches, significant gaps remain in how to develop and assess this competence.

In the current business and educational landscape, innovability positions itself as a fundamental concept for achieving sustainable and competitive development. This term, which merges "innovability" and "sustainability," not only refers to the creation of novel products or services but also involves a deep integration of sustainability across all aspects of the innovation process (De la Vega & Barcellos de Paula, 2021). Innovability extends beyond traditional approaches to innovation, as it requires a reconfiguration of business models and organizational strategies to make sustainability a central axis (Zucchella et al., 2024). This ensures that new ideas and solutions not only generate economic benefits but also have a lasting positive impact on the environment and society (De Tommaso & Pinsky, 2022). Despite advances in its adoption as a strategy, the understanding of innovability as a competence remains limited, highlighting the need for further theoretical and methodological development to clearly delineate it.

Understanding innovability as a competence is crucial for driving sustainable competitiveness in a constantly changing world. However, as a relatively new concept, it is often confused with terms like skill, capability, and creativity (Chang, 2024). Therefore, more theoretical development is needed to clearly delineate innovability as a competence and differentiate it from other similar concepts. For innovability to become a central competence, it must permeate all levels of the organization, from senior management to front-line employees. This involves a profound cultural shift where sustainable innovation becomes a fundamental value, and where collaboration, experimentation, and risk-taking are encouraged (Zucchella et al., 2024). Although innovability presents itself as a promising strategy for achieving business success and contributing to sustainable development (De la Vega & Barcellos de Paula, 2021), more empirical evidence is needed to support this claim. A better understanding of this concept and how it is developed at the individual and organizational level would provide business leaders and educational institutions with the tools and knowledge needed to drive sustainable innovation more effectively.

This study aims to identify how universities cultivate innovability competencies and provide evidence-based recommendations for their effective application in the business sector. Despite the growing recognition of innovability's importance, there is a significant gap in the literature regarding how these competencies can be systematically developed and measured within organizations, in higher education and the business sector. This study seeks to address this gap by exploring the following research questions (RQs):

Q1: What characteristics should a leader in innovability possess?
Q2: What specific recommendations can be made for the business sector to develop innovability? and
Q3: What methodologies or instruments are used to identify leadership competencies in innovability?

Through a rigorous analysis of relevant literature, this work intends to shed light on the mechanisms that drive innovability, offering a practical guide to fostering an organizational culture conducive to idea generation, sustainability, and innovation.

Given the increasing pressure on companies to operate sustainably, understanding and developing innovability is crucial not only to maintain competitiveness but also to meet contemporary social and environmental expectations. This work also contributes to the education and training of future leaders by integrating innovability into the curricula of business schools, preparing the next generation to face the challenges of an increasingly complex and sustainability-oriented business environment. Therefore, this study is essential for bridging current gaps in the literature and providing practical tools for implementation. The article is structured as follows: initially, the theoretical framework is presented

with the main concepts related to the topic and the gaps in the literature; then, the methodology used is described, followed by the main results, the discussion of the findings, and finally, the conclusion.

LITERATURE REVIEW

Innovability as a link between innovation and sustainability

In a world where environmental and social challenges are becoming increasingly complex, the need to incorporate sustainability and innovation into business education has never been more critical. This is why the concept of innovability arises, referring to an organization's ability to integrate innovation and sustainability into its strategies and operations, driving progress that generates value for both the company and society and the environment (De la Vega & Barcellos de Paula, 2021). Innovation emerges as a crucial tool for sustaining competitiveness. Effective use of innovation to remain competitive demands identifying inventions, securing funds, and addressing various other factors that incentivise successful adoption of innovation in the market (Loučanová & Olšiaková, 2019). Innovation might serve as a vital asset in the sustainable logistics transition (Ibrahim et al., 2024).

Innovability and innovation leadership share a common foundation in their emphasis on fostering change and creativity within organizations, but they differ significantly in their focus and objectives. While innovation leadership centers on generating novel ideas and solutions, often driven by technological advances or process improvements (Khumalo & Du Plessis, 2023), innovability goes further by explicitly integrating sustainability as a fundamental principle, considering long-term environmental, social, and economic impacts (Zucchella et al., 2024). Although both require visionary leadership that encourages experimentation and collaboration, innovability adopts a more holistic perspective, aligning innovative progress with the well-being of society and the environment (De la Vega & Barcellos de Paula, 2021). Thus, innovability complements innovation leadership by providing a framework that balances novelty and utility with responsibility and sustainability.

Innovability is based on the premise that innovation and sustainability are not contradictory concepts, but rather complement and enhance each other (Zucchella et al., 2024; Valenti et al., 2024). Companies with high innovability are characterized by their ability to identify opportunities in sustainability challenges, developing creative solutions that generate economic, social, and environmental benefits (Dahlgaard-Park & Dahlgaard, 2010). This holistic approach requires a mindset shift in organizations, moving from a short-term profit-focused business model to one that integrates sustainability in all its dimensions.

Empirical studies have recently explored innovability. Zucchella et al. (2024) present a study on collaborations between multinational companies and smaller startups in the energy sector, focusing on "open innovability" as a key strategy for sustainable development. Through an exploratory and qualitative research approach, they conducted in-depth interviews with participating companies. The results revealed that open innovability, through collaboration between companies, is fundamental for driving sustainable innovation in the energy sector. Key factors for the success of these collaborations were identified, such as the retention of technology ownership by smaller companies, the establishment of a shared vision, and the creation of trust relationships. The benefits of innovability were related to small companies' access to resources and capabilities, as well as improvements in their visibility and credibility. The study does not mention leadership in innovability; however, it suggests that leadership capable of articulating a common vision integrating innovation and sustainability is essential to drive innovability. A shared vision should be promoted, so exploring how leaders can articulate a vision that integrates innovation and sustainability clearly and convincingly for all organization members is relevant for future studies.

Innovability allows reconciling profitability with social welfare. This is the case with the Brazilian company Suzano, which implemented shared value strategies such as reinventing products and exploring new markets for sustainable products, implementing sustainable practices throughout its value chain, and working in collaboration with local communities. This allowed it to reconcile profitability with social welfare, using "innovability" as a central axis (Tommaso & Pinsky, 2021). This research uses an exploratory and descriptive qualitative approach, employing the interactive qualitative analysis method through in-depth interviews. The results indicate that Suzano's innovability strategy allowed it to balance profitability with social welfare, establishing itself as a leader in sustainable development in its sector. The benefits of innovability for the company were to generate value for the business and the community, find new innovation opportunities that drove its sustainability strategy, and build trust and legitimacy, which facilitated the implementation of its projects. The study mentions purpose-driven leadership, focused on generating a positive impact on society and the

environment. It suggests that this type of leadership, with its focus on generating social and environmental value, could be fertile ground for innovability. Future studies might analyze how this type of leadership influences organizational culture, decision-making, and the capacity for innovation towards sustainability.

Despite advances in understanding innovability and its applicability in the business environment, there is a clear need for further research into the role of leadership in this context. Companies, along with the private sector, require Higher Education Institutions (HEIs) to train graduates not only with technical skills but also with business and social competencies necessary to face the challenges linked to the SDGs (Sánchez-Carrillo et al., 2021). However, Mouritz et al. (2022) argue that traditional teaching methods are insufficient to prepare leaders in sustainability. Although there is abundant literature on leadership, management, sustainability, innovation, creativity, and complex thinking, the effective integration of these topics remains a challenge (Ramírez-Montoya & Portuguez-Castro, 2024; Ramírez-Montoya et al., 2024). To move towards a more sustainable future, it is crucial to address and develop the competencies that constitute leadership in innovability.

Currently, there are limited studies exploring the practical implementation of innovability in business and higher education, particularly in understanding how these two domains can collaborate to cultivate competencies that drive innovation and sustainability effectively (De la Vega & Barcellos de Paula, 2021; Tommaso & Pinsky, 2021; Zucchella et al., 2024). This gap in research underscores the importance of future studies that explore how leadership can be a key driver for the integration of innovation and sustainability in organizations. Specifically, there is a need to examine the role of higher education institutions in shaping leaders who possess the necessary innovability leadership skills. Understanding how these competencies are developed and applied in real-world business contexts will provide valuable insights for bridging the gap between theoretical frameworks and practical implementation of innovability.

Leadership competencies in innovation and sustainability

Developing leadership competencies in innovation and sustainability is essential to address the challenges of the 21st century. This is a complex process that involves the development of skills, knowledge, and attitudes that enable individuals and organizations to make responsible, ethical, and effective decisions in a constantly changing context (Olivares et al., 2021, p. 67). Sustainability leadership is not solely focused on achieving economic benefits but aims to integrate social and environmental dimensions into decision-making by generating a positive impact on society and the environment (Iqbal & Piwowar-Sulej, 2022; Alam, 2022). Various sources approach this topic from different perspectives. For example, the importance of leadership in creating a shared vision, managing change, and promoting innovation is highlighted, crucial aspects for transitioning towards sustainability (Arif, 2016; Alam, 2022). The role of collaboration with internal and external stakeholders as a key element for building sustainable business models is also mentioned (Bocken et al., 2019). Innovative leadership refers to the process by which leaders inspire and encourage team members to think and act innovatively, thereby driving organizational innovation (Shan, 2024). This kind of leadership involves not only the completion of direct tasks but, more importantly, the creation of an environment supportive of innovation, where leaders act as motivators, supporters, and providers of resources (Akkoç et al., 2022). Despite the importance of leadership in innovation and sustainability training, various limitations hinder its implementation and measurement.

A comparative analysis of the literature on leadership competencies in sustainability and innovation and their measurement methods has identified some limitations. The study by Knight and Paterson (2018) established five groups of competencies related to attitudes and behaviors: integrative operator, results driver, change agent, ethically oriented, visionary thinker, through a quantitative analysis. Findings showed that behavioral competencies evolve over time, necessitating periodic updates to maintain their validity. Additionally, sample size is noted as a limitation requiring further validation.

The study by Muff et al. (2022) aims to identify the elements of sustainable leadership. Results indicated that self-awareness is considered the central element of this competency, and evidence suggests that students improve their performance in responsible leadership after taking relevant courses. The article acknowledges that more research is needed to confirm these findings, and the context of the sample is a limitation for generalizing results, as well as the need for assessments with professionals. Lastly, the study by Armani et al. (2020) identified seven attributes related to the role of sustainable leadership, including leadership, interpersonal skills, sustainability focus, organizational culture, principles, and moral values. The study is exploratory and relies on qualitative case studies, so the findings are not generalizable to all organizations or contexts, and it is recommended to continue investigating these results more deeply and include other participants.

Measuring leadership in innovation and sustainability is a complex process that requires considering various variables, using appropriate measurement instruments, and accounting for the influence of external factors. It is crucial to adopt a holistic and contextualized approach to understand the real impact of leadership in generating long-term value. Overcoming these limitations requires a joint effort by educational institutions, businesses, and governments to create an environment conducive to training leaders capable of guiding society towards a more sustainable future. However, according to the previous literature review, the development of indicators measuring sustainable and innovative leadership competencies is still limited, necessitating ongoing validation and deeper analysis of the components of innovability competency according to the context in which it develops.

Challenges in identifying leadership competencies in innovation and sustainability in Higher Education

Identifying leadership competencies in innovation and sustainability poses challenges due to the complex and multifaceted nature of these concepts. In terms of innovation, it can manifest in various ways, from creating new products and services to implementing more efficient processes (Manzoor et al., 2023). Moreover, innovation does not always yield short-term tangible results, complicating the measurement of both the innovation itself and the leadership that drives it (Lago et al., 2023). Innovation competence was found to mediate the relationship between innovation education and entrepreneurial intention (Iddris et al., 2022). Innovation education helps students to be competent by ensuring how to find innovative objects to start and maintain a new business (Sabarguna, 2017). Moreover, the alignment between entrepreneurial tasks and emerging technologies, such as generative AI tools, has been identified as a key factor in enhancing students' ability to effectively leverage technology (Marchena Sekili & Portuguez-Castro, 2025), thereby optimizing their performance and fostering long-term business sustainability. The scales and questionnaires used to assess leadership in innovation and sustainability must be carefully selected and validated for the specific context (Zhou et al., 2021), making it crucial to establish clear and specific indicators that capture the essence of innovation in a particular context.

Similarly, sustainability encompasses economic, social, and environmental dimensions that require the evaluation of multiple variables and indicators. Assessing the impact of leadership on sustainability involves analyzing how leaders' decisions and actions contribute to long-term objectives in each of these dimensions, which can be a complex and subjective process (Hossain et al., 2024; Iqbal & Piwowar-Sulej, 2022). Perceptions of leadership vary among individuals and groups, and a leader's influence on innovation and sustainability often develops in collaboration with other actors, further complicating the identification and measurement of an individual leader's influence (Zhou et al., 2021). Therefore, a longitudinal and systemic approach is necessary to understand the real impact of leadership on innovation and sustainability, recognizing that these are not isolated events but continuous processes that evolve over time.

The success of innovation and sustainability initiatives can also depend on external factors. Elements such as market conditions, governmental regulations, and resource availability can influence these outcomes (Gozali et al., 2018). Additionally, a leader may have a direct impact on their team but can also indirectly influence other teams or the organization as a whole through organizational culture, policies, and incentive systems, making it challenging to unravel the individual contributions of each actor within this complex web of relationships and processes (Dianingrum et al., 2022). In this context, effectively measuring innovability requires tools and methods that can capture both the direct and indirect influences of leadership on innovation and sustainability through diverse measurement approaches that can offer a more comprehensive view and minimize the limitations of a single instrument.

The role of higher education institutions in developing leadership competencies for innovability.

Modern companies increasingly emphasize sustainability as a strategic priority, seeking leaders who can balance economic growth with social and environmental considerations. Studies reveal that businesses prioritize specific leadership qualities, such as the ability to innovate responsibly, manage diverse teams, and adapt to global challenges (Purcell et al., 2019; Strukelj et al., 2023). Leaders are expected to develop and implement strategies that not only promote organizational success but also address societal challenges like climate change and inequality (Alam, 2022; Manzoor et al., 2023). Moreover, the demand for collaborative and inclusive leadership has grown, with companies requiring individuals who can build alliances, engage stakeholders, and navigate complex interdependencies.

To meet these demands, HEIs have integrated sustainability and innovation into their academic and co-curricular programs. Many universities now offer courses and specializations that focus on topics such as corporate social responsibility, circular economy, and social innovation (Iqbal & Piwowar-Sulej, 2022; Hueske & Pontoppida, 2020).

Leadership programs have also evolved to include training on transformational leadership, equipping students with the skills to lead organizational change and foster sustainable practices (Strukelj et al., 2023). University business incubators provide a platform for students to apply their knowledge by supporting startups that address sustainability challenges. These incubators offer mentorship, funding opportunities, and access to networks, helping students develop innovative solutions with practical applications (Almansour, 2022). Additionally, HEIs establish partnerships with companies to create experiential learning opportunities, such as internships and real-world sustainability projects, which allow students to engage directly with the challenges faced by businesses.

Despite these efforts, some studies suggest that graduates often lack the practical skills required to address sustainability challenges in a business context. For example, while students may learn about sustainability frameworks, they may not fully understand how to implement them in complex organizational environments (Mzyece et al., 2021). This highlights a need for greater collaboration between HEIs and the business sector to align training programs with industry demands (Purcell et al., 2019). By strengthening this collaboration, HEIs can ensure that their graduates are well-prepared to address the multifaceted challenges of innovability in the workplace.

This study is designed to deepen the understanding of innovability competence, a crucial emerging concept for integrating sustainability and innovation into business practices. The objectives are to identify the essential components of innovability competence, provide evidence-based recommendations for its development in corporate environments, and critically evaluate current methodologies and tools used for its measurement. Areas for improvement are highlighted, and opportunities for future research are identified. This research is significant for business leaders and executives, human resources and organizational development professionals, as well as academics in universities and business schools who seek to integrate and teach leadership competencies in innovation and sustainability effectively.

METHODOLOGY

A systematic review typically requires considerably more effort than a traditional review. The process is akin to primary scientific research and involves the meticulous and systematic gathering, measuring, and synthesizing of data (Sage Research Methods, 2020). The Systematic Literature Review (SLR) conducted for this research followed the protocol outlined by Kitchenham and Charters (2007), which involves reviewing a protocol to specify the research question. Inclusion and exclusion criteria were determined, and three research questions (RQ: 1-3) presented in the Introduction section were established for analyzing the articles. The systematic approach ensures that the review is not only comprehensive but also objective and replicable, providing a solid foundation for drawing reliable conclusions and making informed recommendations that contribute to the field of study. By addressing these research questions, the review aims to illuminate the pathways through which organizations and their leaders can harness the dual powers of innovation and sustainability to drive meaningful progress.

Search strategy

The search was conducted in the Scopus and Web of Science (WOS) databases using the following search string for both databases: "sustainability AND innovation AND leadership AND business AND 'higher education'". This query yielded 16 articles from Scopus and 64 from WOS. After removing eight duplicate articles and one that did not meet the inclusion criteria. Only scientific articles were retained, a total of 53 articles remained for analysis based on the three research questions. Figure 1 illustrates the steps followed to arrive at the total number of articles for analysis. This systematic approach ensures the review comprehensively encompasses the relevant literature, addressing the defined research questions effectively.

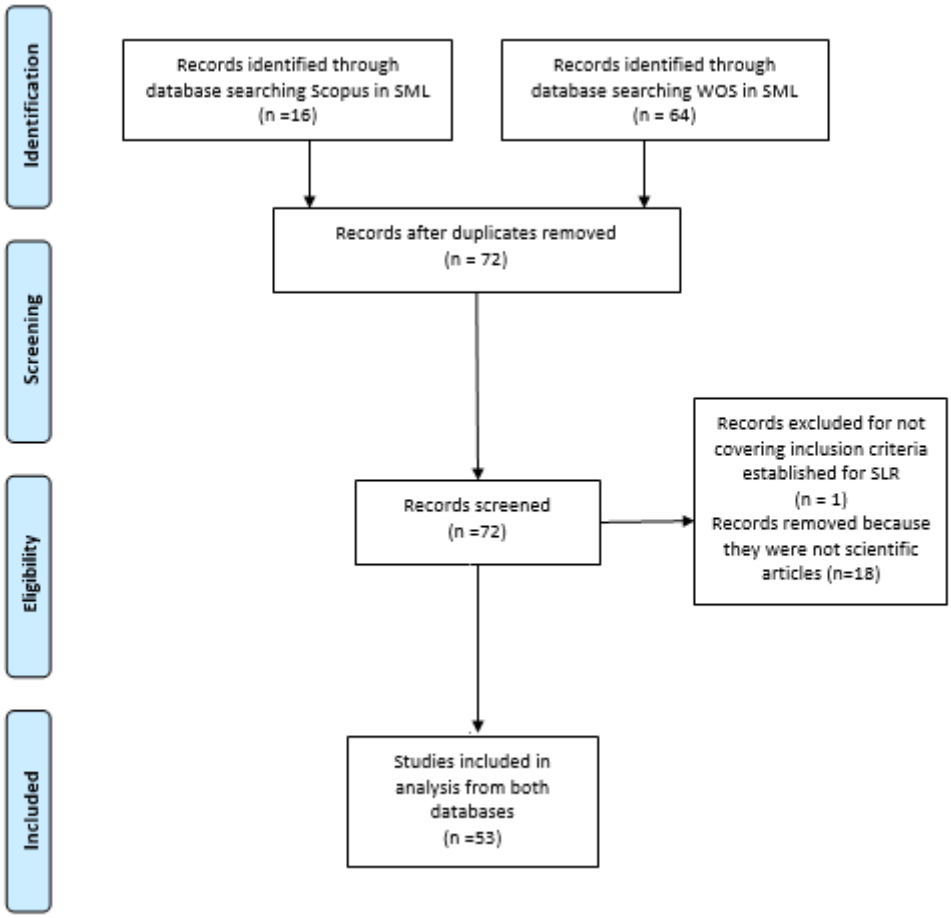

Figure 1. Prisma flow diagram to show the search strategy

Source: Developed by authors and based on Page et al. (2021).

Inclusion and exclusion criteria

The inclusion and exclusion criteria are set with the purpose of capturing and incorporating the questions that the Systematic Literature Review (SLR) aims to answer. The criteria are designed to enhance the efficiency of article retrieval for analysis. Table 1 displays the inclusion and exclusion criteria that were followed.

Table 1. Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Papers published between 2015 and 2024	Those papers prior to the 2015
Scientific papers	Outreach articles
Papers containing the keywords sustainability, innovation, leadership, business and "higher education"	Papers not related to the research topic

These criteria facilitate a targeted and efficient search, ensuring that the articles selected for review are directly pertinent to the research questions of the SLR, thereby enhancing the overall quality and relevance of the review process. This methodical approach helps in building a solid foundation for synthesizing the existing literature and identifying gaps for future research.

Phases of the research process

- Identification: The search string initially identified 16 articles in Scopus and 64 articles in WOS.
- Selection: The articles were selected based on their relevance to higher education studies and their potential to address the research questions, yielding a total of 80 articles. Duplicate articles were removed, leaving 72 articles.

- Inclusion: One article that did not meet the inclusion criteria was removed, and only the scientific articles were included, resulting in a final count of 53 papers. Once the documents were selected, a content analysis was conducted to address the research questions, categorizing the information to support the analysis. The thematic synthesis involved coding the selected articles based on predefined categories related to innovability leadership competencies. Each article was systematically reviewed, and themes were identified through an iterative process, ensuring that both explicit and implicit themes were captured. The content analysis facilitated the identification of recurring patterns and gaps in the literature, allowing for a more comprehensive synthesis of the findings.
- Reporting: The results of the in-depth analysis of the articles are presented in tables and graphs to make the information more comprehensible to readers, and explanatory text is included beneath the figures and tables to supplement the information.

RESULTS

The answers to the research questions based on the analysis of the 53 studies consulted are presented below.

What characteristics should a leader in innovability possess?

To answer the characteristics of an innovability leader, the consulted articles were examined to determine the main characteristics of a leader in innovation and sustainability. From this analysis, five key categories were deduced, which are detailed in Table 2.

Table 2. Characteristics of innovability leadership

Category	Authors
Strategic Leadership and Innovation Vision	Purcell et al., 2019; Kompella, 2024; Arif, 2016; Camacho-de la Parra et al., 2023; Mzyece et al., 2021; Lago et al., 2023; Khumalo & Du Plessis, 2023; Barykin et al., 2023; Rinaldi et al., 2018; Hannon et al., 2019; Costa et al., 2022
Innovation Culture and Collaboration	Arif., 2016; Camacho-de la Parra et al., 2023; Almansour, 2022; Iqbal & Piwowar-Sulej, 2022; Manzoor et al., 2023; Dianingrum et al., 2022; Strukelj et al., 2023; Hossain et al., 2024; Taleb et al., 2023; Lago et al., 2023; McAdam et al., 2021; Rinaldi et al., 2018
Education and Training in Innovation and Entrepreneurship	Suparno et al., 2024; Iqbal & Piwowar-Sulej, 2022; Saif, Goh et al., 2023; Zhou et al., 2021; Wakkee, van der Sijde et al., 2019; Costa et al., 2019; Yu, Qiu and Gupta, 2022
Sensitivity to Megatrends and Sustainable Practices	Camacho-de la Parra et al., 2023; Eustaquio et al., 2024; Purcell et al., 2019; Ritchie-Dunham et al., 2023; Wardhani & Rahadian, 2021; Islam & Iyer-Raniga, 2023; Tan & Omar, 2022; Alam, 2022; McAdam et al., 2021; Ritchie-Dunham et al., 2023
Development of Interpersonal and Emotional Leadership Skills	Islam & Iyer-Raniga, 2023; Alam, 2022; Dianingrum et al., 2022; McAdam et al., 2021; Shafait, Meyer & Sroka, 2021; Wakkee et al., 2019; Manzoor et al., 2023; Lago et al., 2023; Kompella, 2024; Khumalo & Du Plessis, 2023; Ge & Li, 2019

Strategic leadership and innovation vision centers on leaders who adopt a strategic approach focused on sustainability and innovation. This approach is oriented towards achieving the SDGs and solving real-world problems (Mzyece et al., 2021; Purcell et al., 2019). Such leadership embodies a holistic vision that integrates innovation with environmental and social impact (Arif, 2016; Barykin et al., 2023; Camacho-de la Parra et al., 2023; Lago et al., 2023), managing change with a strategic and transformative mindset (Costa et al., 2022; Hannon et al., 2019; Kompella, 2024). These leaders seek to turn sustainability challenges into opportunities for innovation, enabling them to implement effective actions and ensure long-term sustainable processes (Khumalo & Du Plessis, 2023; Rinaldi et al., 2018).

Innovation culture and collaboration is characterized by the importance of developing an organizational environment where innovation, collaboration, and co-creation are essential elements. In this area, a culture that engages all stakeholders and builds strong partnerships is fostered (Almansour, 2022; Arif, 2016; Iqbal & Piwowar-Sulej, 2022; Manzoor et al., 2023) to promote experimentation and the generation of innovative ideas (Strukelj et al., 2023; Taleb et al., 2023). Projects are developed that create a positive impact through co-creation, reflecting values of care, mutual respect, and respect for the environment (Camacho-de la Parra et al., 2023; Dianingrum et al., 2022; Rinaldi et al., 2018). Additionally, there

is flexibility and speed in responding to environmental changes, adapting strategies, business models, and innovation processes (Hossain et al., 2024; Lago et al., 2023; McAdam et al., 2021).

Education and training in innovation and entrepreneurship focuses on the value of education in developing innovative and sustainable solutions. The emphasis is placed on having a high creative potential and creating an environment that fosters the generation of innovative ideas (Ashal et al., 2023; Taleb et al., 2023; Zhou et al., 2021). Continuous training to develop the skills necessary for sustainable and effective solutions is essential (Ong & Khan, 2023; Suparno et al., 2024; Wakkee et al., 2019). This approach also includes ongoing investment in professional development, preparing leaders who can steer the transformation towards innovation and sustainability (Costa et al., 2022; Iqbal & Piwowar-Sulej, 2022; Yu et al., 2022).

Sensitivity to megatrends and sustainable practices addresses the need to understand how global megatrends such as climate change, emerging technology, and globalization impact systems and demand innovative and sustainable solutions. This category promotes a commitment to ethics and values that guide the development of sustainable solutions (Alam, 2022; Camacho-de la Parra et al., 2023; Eustaquio et al., 2024). The importance of adopting a strategic approach that is aware of the megatrends impacting the planet (Purcell et al., 2019; Ritchie-Dunham et al., 2023; Wardhani & Rahadian, 2021) is emphasized, allowing for the identification and management of ecological practices such as the circular economy (Islam & Iyer-Raniga, 2023). Moreover, the integration of sustainability into curriculum is promoted, guiding the development of specific competencies that enable individuals to confront and lead in the face of growing environmental and social challenges (Alam, 2022; Eustaquio et al., 2024; Igwe, 2022; McAdam et al., 2021).

Emotional leadership and development of interpersonal competencies highlights the importance of leaders who not only lead by example and inspire others but also empower and effectively motivate their teams. This leadership approach involves building strong relationships based on trust, empathy, and collaboration, adopting an innovative and global mindset that focuses on customer needs and the well-being of employees and stakeholders (Alam, 2022; Islam & Iyer-Raniga, 2023). These leaders excel in emotional intelligence, knowledge management skills, and a commitment to sustainability, which are essential for fostering an environment where benevolence and integrity prevail (Dianingrum et al., 2022; McAdam et al., 2021; Shafait et al., 2021). They also actively promote creativity and experimentation, continuously preparing themselves through professional development and adapting agilely to environmental changes (Ge & Li, 2019; Lago et al., 2023; Manzoor et al., 2023). This type of leadership not only improves the work environment but also facilitates access to complementary resources and fosters extensive cooperation, which is crucial for organizational success in a constantly evolving world (Ge & Li, 2019; Kompella, 2024; Khumalo & Du Plessis, 2023).

According to the literature reviewed, an innovability leader should exhibit a combination of strategic vision, the ability to foster collaboration, a commitment to sustainability, and advanced interpersonal skills. These characteristics enable them to transform challenges into innovative opportunities that benefit both their organization and the broader environment. In practice, this should translate into leading by example, empowering teams, promoting a culture of creativity and experimentation, and developing sustainable solutions that respect and enhance both human and natural resources. In this sense, innovability is a comprehensive approach that aligns business needs with ethical and environmental imperatives, thereby ensuring a positive and lasting impact on society and the economy.

What specific recommendations can be made for the business sector to develop innovability?

To identify recommendations for developing innovability in companies, the consulted articles were examined to determine the best practices for integrating innovation and sustainability into organizations. From this analysis, five key categories were deduced, which are detailed in Table 3.

Table 3. Recommendations for developing innovability in companies

Category	Authors
Leadership and Organizational Culture	Ritchie-Dunham et al., 2023; Kompella, 2024; Camacho-de la Parra et al., 2023; Eustaquio et al., 2024; Khumalo & Du Plessis, 2023; Dianingrum et al., 2022; Ge & Li, 2019; Lago et al., 2023; Liu et al., 2024; Suparno et al., 2024
Education, Training, and Skill Development	Arif, 2016; Camacho-de la Parra et al., 2023; Almansour, 2022; Iqbal & Piwowar-Sulej, 2022; Manzoor et al., 2023; Zhang, & Ma, 2023; Dianingrum et al., 2022; Strukelj et al., 2023; Hossain et al., 2024; Taleb et al., 2023; Lago et al., 2023; McAdam et al., 2021; Rinaldi et al., 2018

Category	Authors
Innovation and Sustainability in Operations	Suparno et al., 2024; Iqbal & Piwowar-Sulej, 2022; Taleb et al., 2023; Ong,& Khan, 2023; Zhou et al., 2021; Wakkee et al., 2019; Costa et al., 2022; Yu et al., 2022
Collaboration and Continuous Learning	Arif, 2016; Almansour, 2022; Mzyece et al., 2021; Khumalo & Du Plessis, 2023; Islam & Iyer-Raniga, 2023; Lago et al., 2023; Igw et al., 2022; Kompella, 2024; Đorđević, 2021; Ritchie-Dunham et al., 2023; Purcell et al., 2019
Evaluation, Monitoring, and Adaptability	Sann et al., 2023; Strukelj et al., 2023; Islam & Iyer-Raniga, 2023; Zhou et al., 2021; Ritchie-Dunham et al., 2023; Filippaios & Benson, 2019; Igwe et al., 2022; Lago et al., 2023; Liu et al., 2024; Shafait et al., 2021; Wakkee et al., 2019

In the category of leadership and organizational culture, it is crucial for companies to integrate sustainability into their corporate mission, establishing a strong framework that promotes a culture of innovation and collaboration at all levels of the organization. This involves fostering leadership that is not only strategic and collaborative but also develops and empowers other leaders within the company to encourage adaptability and cooperation among their teams (Ge & Li, 2019; Lago et al., 2023; Ritchie-Dunham et al., 2023). Moreover, it is essential to cultivate an environment where innovation and employee well-being are valued (Dianingrum et al., 2022), actively involving employees in decision-making processes so that they feel more engaged and motivated (Lago et al., 2023; Liu et al., 2024; Saif et al., 2023), as well as promoting a diverse and inclusive environment (Camacho-de la Parra et al., 2023). Finally, continuous training of business leaders in sustainability principles is essential to ensure that the vision of innovability remains relevant and evolves with global and market demands (Eustaquio et al., 2024; Kompella, 2024; Khumalo & Du Plessis, 2023; Suparno et al., 2024).

In the category of education, training, and skill development, it is fundamental for companies to invest in business education to promote a culture of continuous innovation. This includes training employees in quality management methodologies to optimize processes and apply innovation efficiently to problem-solving (Arif, 2016; Alam, 2022; Lisdiono et al., 2023; Tan & Omar, 2022; Zheng et al., 2024;). Additionally, it is essential to develop skills that enable employees to innovate while understanding the social impact of their innovations, ensuring that business initiatives contribute positively to society (Kompella, 2024). Integrating sustainability into leadership development programs helps align business goals with global sustainability objectives (Iqbal & Piwowar-Sulej, 2022; Khumalo & Du Plessis, 2023; Manzoor et al., 2023; Ritchie-Dunham et al., 2023), while fostering emotional intelligence and knowledge management prepare employees to handle complex challenges and collaborate effectively (Liu et al., 2024; Shafait et al., 2021; Wakkee et al., 2019). Finally, promoting a culture of self-awareness and ethical values is crucial for maintaining a work environment that values integrity and mutual respect, essential elements for a true culture of innovation (Alam, 2022; Dianingrum et al., 2022).

In the category of innovation and sustainability in operations, companies should focus on integrating sustainability at the core of innovation. This includes using eco-friendly materials and reducing environmental impacts across all aspects of production and operations (Islam & Iyer-Raniga, 2023; Khumalo & Du Plessis, 2023; Strukelj et al., 2023). It is essential to develop products and services that are not only innovative but also sustainable, ensuring that each new offering contributes positively to the environment and society (Ge & Li, 2019; Taleb et al., 2023; Zhou et al., 2021). Adopting circular economy principles is another key strategy, allowing companies to close production and consumption loops to maximize resource efficiency (Arif, 2016; Islam & Iyer-Raniga, 2023; Qin, Duan, Al-Hourani & Alsaadi, 2022). Furthermore, promoting the creation of sustainable value through value-based business models can differentiate a company in the market, while implementing advanced Industry 4.0 technologies can enhance business performance and facilitate eco-innovation, enabling operations to be more agile and less harmful to the environment (Filippaios & Benson, 2019; Lago et al., 2023; McAdam et al., 2021).

In the category of collaboration and continuous learning, it is crucial for companies to foster both internal and external collaboration to unlock new innovation opportunities. Creating dedicated spaces for knowledge exchange and interdisciplinary collaboration can catalyze creativity and accelerate the development of innovative solutions (Almansour, 2022; Khumalo & Du Plessis, 2023). Establishing strategic partnerships within the innovation ecosystem, including collaborations with other companies, universities, and institutions, is fundamental to integrating diverse perspectives and expertise that enrich projects and reinforce sustainability goals (Igwe et al., 2022; Islam & Iyer-Raniga, 2023; Lago et al., 2023). Additionally, promoting a culture of collaboration among employees is essential to maintain a vibrant, innovation-oriented work environment where idea exchange becomes the norm (Đorđević, 2021; Kompella, 2024; Mzyece et al., 2021). Lastly, collaborating through specific partnerships to address sustainability challenges allows companies to

adopt a more integrated and effective approach to solving complex problems, ensuring that joint efforts lead to more substantial and lasting results (Purcell et al., 2019; Ritchie-Dunham et al., 2023).

In the category of evaluation, monitoring, and adaptability, it is essential for companies to implement robust tracking and evaluation systems for their innovability initiatives. This involves using specifically tailored indicators to measure progress and the real impact of innovations in terms of sustainability and business effectiveness (Islam & Iyer-Raniga, 2023; Strukelj et al., 2023; Zhou et al., 2021). Additionally, it is crucial to continuously reassess and adjust training programs to ensure they are aligned with the evolving needs of the business environment, enabling employees to stay ahead in relevant skills and knowledge (Alam, 2022; Filippaios & Benson, 2019; Igwe et al., 2022). Establishing clear and objective metrics helps organizations better understand the return on investment in innovation and make proactive adjustments (Lago et al., 2023; Sann et al., 2023). On the other hand, developing organizational agility to quickly respond to environmental changes is fundamental to maintaining competitiveness and market relevance (Lago et al., 2023). Finally, fostering a culture that values problem-solving and internal entrepreneurship encourages employees to take initiative and seek creative solutions to challenges, thus driving a continuous cycle of innovation and improvement (Liu et al., 2024; Shafait et al., 2021; Wakkee et al., 2019).

What methodologies or instruments are used to identify leadership competencies in innovability?

To answer the question of what methods or instruments are being used to identify innovability leadership competence, articles that address methods/instruments for identifying both innovation leadership competence and sustainability leadership competence were considered. The results are presented in Table 4.

Table 4. Methods/Instruments for identifying innovability leadership competence

Method	Authors
Quantitative method	Suparno et al., 2024;Camacho-de la Parra et al., 2023; Eustaquio et al., 2024; Iqbal & Piwowar-Sulej, 2022; Manzoor et al., 2023; Khumalo & Du Plessis, 2023; Đorđević, 2021; Taleb et al., 2023; Alam, 2022;Ong & Khan, 2023; Zhou et al., 2021; Zheng et al., 2024; Lisdiono et al., 2023; Filippaios & Benson, 2019; Alyahya et al., 2022; Liu et al., 2024; Shafait et al., 2021; Qin et al., 2022; Liu, Alnafrah & Zhou, 2024; Gugissa et al., 2021; Yu et al., 2022
Qualitative method	Purcell et al., 2019; Ritchie-Dunham et al., 2023; Kompella, 2024;Almansour, 2022; Mzyece et al., 2021; Alam, 2022; Islam & Iyer-Raniga, 2023; Ge & Li, 2019; Wardhani & Rahadian, 2021;Tennakoon et al., 2023; Tan & Omar, 2022; McAdam et al., 2021; Rinaldi et al., 2018; Buono et al., 2015; Sipos et a.l, 2021; Wakkee et al., 2019; Azalanzazllay et al., 2022; Hannon et al., 2019; Costa et al., 2022
Mixed methods	Pepin et al., 2024; Lago et al., 2023; Barykin et al., 2023; Sann et al., 2023
Bibliometric study	Strukelj et al., 2023
Literature review	Hueske & Pontoppida, 2020; Igwe et al., 2022

Among the articles that employed a quantitative method, several used measurement instruments, such as questionnaires. For example, Suparno et al. (2024) utilized a questionnaire to measure the relationship between business education, creativity, and innovation. Eustaquio et al. (2024) developed a questionnaire aimed at understanding how sustainability leadership (SL) and transformational leadership (TL) influence social innovation and the teaching of sustainability in HEIs. In the study by Dianingrum et al. (2022), a questionnaire collected subordinate responses regarding the paternalistic leadership of their superiors, covering three dimensions: authoritarianism, benevolence, and morality. Hossain et al. (2024) used a questionnaire to gather data from a sample of Malaysian manufacturing companies. Taleb et al. (2023) employed a structured questionnaire to collect data from micro-entrepreneurs in Malaysia, with the objective of testing the effects of entrepreneurial leadership, opportunity recognition, and innovation capacity on the business success of microenterprises. Ong and Khan (2023) used a questionnaire to identify competencies related to green leadership, green creativity, and green intrinsic motivation in university students. Qin et al. (2022) used a questionnaire distributed to managers, heads, and assistants of Turkish pharmaceutical companies, which included questions related to the three dimensions of Total Quality Management (TQM): customer focus, process management, and leadership. Ashal et al., 2023) employed a questionnaire with 54 statements, 35 of which were divided into four dimensions: conducive learning environment, learning processes and practices, leadership that reinforces learning, and creating a learning structure. The remaining 19 statements were divided into five dimensions: new business initiatives, innovation capacity, self-renewal, proactivity, and risk-taking.

In other quantitative studies consulted, no specific instrument was mentioned (Alam, 2022; Arif, 2016; Camacho-de la Parra et al., 2023; Iqbal & Piwowar-Sulej, 2022; Zhou et al., 2021). In Đorđević's (2021) study, data were collected through paper and online surveys targeting leaders and members of public and private universities. Regarding the techniques used, Jayashree et al. (2022) study was conducted using a Partial Least Squares Structural Equation Modeling (PLS-SEM) with data collected from 314 Malaysian SMEs. The article by Zheng et al. (2024) involves a descriptive study to globally analyze carbon emissions, followed by cross-sectional dependence (CD) statistics and slope heterogeneity (SH) analysis. A cross-sectional quantitative survey was conducted in Lisdiono et al. (2023) research; Barykin et al. (2023) applied a fuzzy decision-making modeling technique; a cross-sectional research design is presented in Shafait et al. (2021) article; Liu et al. (2024) article used Data Envelopment Analysis (DEA) with bias correction and unsupervised machine learning techniques across 30 OECD countries. In Yu et al. (2022) article, a procedure is described for evaluating the effectiveness of a supplier training program, which proved useful in a practical situation faced by an original equipment manufacturer (OEM) in the automotive industry.

In the articles that utilized a qualitative methodological approach, the case study technique was prominently used (Azalanzazllay et al., 2022; Buono et al., 2015; Costa et al., 2022; Ge & Li, 2019; Islam & Iyer-Raniga, 2023; Kompella, 2024; McAdam et al., 2021; Mzyece et al., 2021; Purcell et al., 2019; Ritchie-Dunham et al., 2023; Strukelj et al., 2023; Tennakoon et al., 2023; Sipos et al., 2021;). On the other hand, Almansour's (2022) article describes a qualitative study aimed at understanding entrepreneurs' perceptions of the support received in university business incubators and its alignment with the SDGs and technological innovations. Alam (2022) used a qualitative approach, employing interviews and document analysis to collect data on leadership and governance structures in private universities in Bangladesh. Wardhani and Rahadian (2021) conducted a qualitative content analysis to explore the sustainability strategies of palm oil companies in Indonesia and Malaysia. A phenomenological approach was applied to examine the lived experiences of participants working or having worked in Traditional Chinese Medicine (TCM) clinics in Singapore in Tan and Omar's (2022) article. In Wakkee et al. (2019) article, multiple observations of complex processes were conducted, useful for theory building. Hannon et al. (2019) research employed a collaborative philosophy and the NIZAC strategy and action framework, which had a positive potential in challenging and supporting the group of participating universities and organizations, in collaboration with host cities/communities/business sectors.

Only four articles were found to use a mixed-methods approach. Pepin et al. (2024) article focuses on the creation and evaluation of a tool called the "Responsible Business Model Canvas" (RBMC) to integrate sustainability into business models. Lago et al. (2023) research analyzes the role of cooperation and technological orientation in the innovation capacity of startups and presents the German Startup Monitor (GSM). Barykin et al. (2023) study applied a fuzzy decision-making modeling technique. The UNIQUAL scale was developed and validated in the article by Sann et al. (2023).

DISCUSSION

In the current context, innovability emerges as a relevant approach for companies to achieve sustainable and innovative development, and the development of leaders with this competence is crucial to achieving it. Regarding the first question related to the characteristics that a leader in innovability should possess, the literature reveals that there is no clear definition of leadership with this competence, and there are also challenges in its delimitation and conceptualization. As shown in Table 2, the literature review carried out in this research identified five categories that can be considered key elements of the innovability competency: a strategic vision, the ability to foster collaboration, a commitment to sustainability, and advanced interpersonal skills. These characteristics could be identified through the analysis of articles related to innovation and sustainability. For instance, Tommaso and Pinsky (2022) emphasize the importance of purpose-driven leadership as a key element in translating sustainability into strategy, directly influencing profitability, social well-being, and sustainable economic development. Additionally, collaboration is identified as a fundamental component for the success of innovability. Zucchella et al. (2024) indicate that cooperation among companies can drive sustainable innovation. Furthermore, trust emerges as a crucial factor in collaboration for innovation, particularly in the context of open innovation, where establishing solid trust relationships is essential for sharing knowledge and resources, yet this study further suggests that fostering a culture of collaboration is not just beneficial but essential for sustaining innovability in the long term. Although the literature does not yet offer a unified definition of innovability leadership, it is suggested that leaders in this area should possess a strategic vision, the ability to foster collaboration, a firm commitment to sustainability, and advanced interpersonal skills.

Developing innovability within companies requires a multifaceted approach that integrates innovation and sustainability into the culture, processes, and business strategy. Regarding the second question related to recommendations for developing innovability in companies, few empirical studies were found on the implementation of this approach. As shown in Table 2, the review of articles with recommendations for implementing innovation and sustainability allowed for the delineation of some guidelines, which are related to leadership development and organizational culture, education and skill development, innovation and sustainability in operations, collaboration, and evaluation. These actions, derived from the literature, are noted by the authors as beneficial for promoting these behaviors within the organization (Almansour, 2022; Iqbal & Piwowar-Sulej, 2022; Ritchie-Dunham et al., 2023). However, the scarcity of empirical studies supporting the implementation of this multifaceted approach in companies makes it difficult to identify best practices and measure success (Kompella, 2024). These findings are important because they allow corroborating the importance of innovation and sustainability in organizations, and above all, they constitute evidence to justify that in the field of business it is necessary that both concepts are integrated, since the literature review allowed identifying that in the challenging context we are currently facing, success in the economic and business field cannot be separated from social and environmental welfare, thus setting a guideline to emphasize the relevance of the implementation of innovation in business and its inclusion in the curricula of higher education institutions. Despite this, the existing literature offers a valuable theoretical framework for further exploring the innovability approach, and the development of more empirical studies will provide a more comprehensive understanding of the challenges and opportunities in building a sustainable future through innovation and sustainability.

In this research, few instruments were identified that establish a link between innovation and sustainability in their measurement, and it was found that there are no instruments specifically designed to measure innovability. The SLR identified two articles that include innovation and sustainability in their measurement: the study by Eustaquio et al. (2024), which aims to understand how sustainability leadership (SL) and transformational leadership (TL) influence the level of social innovation and the teaching of sustainability in Higher Education Institutions (HEIs), and the study by Almansour (2022), which seeks to understand entrepreneurs' perceptions of the support received in university business incubators and its alignment with the SDGs and technological innovations. The concept of innovability refers to an organization's ability to integrate innovation and sustainability into its strategies and operations, driving progress that creates value for both the company and society and the environment (De la Vega & Barcellos de Paula, 2021). The results of this study highlight the need to design and validate an instrument focused on measuring innovability competence in higher education students to establish strategies that strengthen this competence, which is important in the business environment and for generating social benefits.

CONCLUSION

In the studies analyzed, findings on leadership competencies in innovation and sustainability were identified, but rarely addressed jointly, and there remains no solid research base on innovability as a distinct concept. Innovability bridges innovation and sustainability, offering a framework for aligning progress with environmental and social responsibility. However, its implementation faces challenges such as the lack of standardized metrics, limited empirical evidence, and a need to identify specific leadership skills that drive innovability. These include strategic vision, fostering collaboration, commitment to sustainability, and emotional intelligence. While some cases, like Suzano (Tommaso & Pinsky, 2021), illustrate its potential, more research is needed to develop measurement tools, compare innovability with established leadership models, and document its application in diverse contexts. These steps are crucial to solidify innovability as a valuable construct in business and education.

The study reaffirms the importance of innovability leadership competencies and proposes a conceptual framework for their integration into organizations. The responses to the study's three key questions—regarding the definition of innovability, the characteristics of leadership in this area, and the recommendations for implementing it—underscore the need for further theoretical clarification. In this context, innovability is presented as a dynamic and adaptable construct that relies not only on the technical and strategic skills of leaders but also on their ability to influence organizational culture. This theoretical approach can serve as a foundation for future studies aimed at developing more integrated and precise models of innovability leadership.

Furthermore, the identification of five main categories of innovability leadership suggests that these characteristics could be studied in greater depth and connected with specific organizational outcomes. This would enrich the theory

in this emerging field by providing a more detailed understanding of how these competencies impact innovation and sustainability within companies. Therefore, there is an urgent need to continue researching these theoretical aspects to build a more solid and coherent conceptual framework that guides both future research and business practice.

Additionally, this study highlights the critical role of HEIs in cultivating innovability competencies. HEIs are uniquely positioned to bridge the gap between theoretical frameworks and practical applications, equipping future leaders with the skills needed to address sustainability and innovation challenges in organizations. By embedding sustainability and innovation within academic curricula, fostering experiential learning opportunities, and promoting interdisciplinary approaches, HEIs contribute to advancing both the theoretical understanding and practical implementation of innovability leadership. Further research could explore how the educational strategies employed by HEIs directly influence the development of these competencies and their subsequent impact on organizational success.

In practical terms, this study offers clear guidelines for companies and educational institutions to design leadership training and development programs that integrate innovability. The responses to the key questions highlight the importance of fostering a collaborative and trusting environment within organizations. These implications suggest that companies should adopt more structured approaches to integrating innovation and sustainability into their business strategies by implementing purpose-driven leadership programs and creating collaboration mechanisms that overcome the barriers of power asymmetry.

For educational institutions, these findings imply the need to incorporate content and practices that prepare students to lead with a holistic and sustainable vision. Additionally, the review of articles allowed for the delineation of practical guidelines that, while derived from the literature, require empirical validation to ensure their effectiveness in different business contexts. This approach provides an initial framework that organizations can use to promote innovability, but it also underscores the need to continue exploring its application in practice through more specific and contextually relevant empirical studies.

The development of innovability competencies has significant implications for business schools, especially in the training of leaders who can integrate innovation and sustainability into business strategies. Business schools, as centers for training future leaders, play a crucial role in preparing their students to face the contemporary challenges of the global business environment. Incorporating innovability into academic programs means not only teaching traditional management and leadership techniques but also fostering a mindset that integrates sustainability as a central axis of innovation.

The research results also highlighted the utility of designing and validating an instrument to measure innovability competence, as it is a valuable concept to integrate into companies, linking innovation and entrepreneurship with sustainability. This not only benefits the profitability of the organizations where it is implemented but also generates social value. Having a measurement instrument will enable the development of strategies that allow higher education students to strengthen their knowledge, skills, and attitudes toward innovability, preparing them to be leaders in companies that drive this vision of promoting both innovation and sustainability: innovability.

The study encountered limitations, such as the scarcity of empirical studies addressing the implementation of innovability leadership within companies, highlighting a gap in the literature that needs to be addressed. The responses to the study's questions indicate that while there are promising theoretical frameworks, the lack of empirical validation limits their applicability in real-world scenarios, making it difficult to identify best practices and accurately measure their success.

The absence of specific measurement tools to evaluate innovability competence represents another significant limitation. This lack hinders the empirical validation of the proposed theoretical findings and limits companies' ability to effectively assess and develop these competencies in their leaders. Therefore, it is essential for future research to focus on developing methodologies and evaluation tools that can be adapted to different organizational and cultural contexts.

Additionally, the study relied solely on a review of the existing literature, which, while comprehensive, does not provide insights from practical fieldwork. Future research should incorporate interviews with business leaders to better understand their needs regarding innovability competencies. This approach would allow for a more nuanced understanding of the specific skills and attributes required in different organizational settings. Moreover, analyzing the curricula of business programs in HEIs would provide valuable insights into how these competencies are being addressed, and whether existing academic programs are aligned with industry demands.

Directions for future research focus on the need to address the gaps identified in this study. It is crucial to develop empirical studies that validate the innovability leadership characteristics identified in the literature and explore how these characteristics can be cultivated and evaluated in various organizational settings. The responses to the key study questions

suggest that future research should focus on creating evaluation tools that allow for accurate and reliable measurement of innovability competencies.

It would also be valuable to investigate how cultural and sectoral contexts influence the effectiveness of innovability leadership. This could lead to the customization of training and development strategies based on the specific needs of each organization. In this way, not only will the theoretical understanding of the subject be expanded, but practical tools will also be provided, enabling companies to lead in an increasingly complex and competitive environment, achieving a balance between innovation, sustainability, and business success.

Finally, the impact of developing innovability competencies in business schools is crucial, as these institutions must prepare future leaders to face global challenges centered on sustainability and innovation. Integrating the innovability approach into the curriculum involves adapting academic programs to include purpose-driven leadership, collaboration, and trust-building, equipping students with essential skills to lead in an ever-evolving business environment. This not only enhances the employability of graduates but also positions business schools as pioneers in education for sustainable business development.

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May Portuguez-Castro: Conceptualization, Formal Analysis, Literature Investigation, Methodology, Project Administration, Software, Supervision, Validation, Visualization, Writing Original Draft, Writing – Review & Editing. **Isolda Margarita Castillo Martínez**: Data Curation, Literature Investigation, Validation, Visualization, Writing Original Draft – Review & Editing.

Conflicts of interest

The authors declare no conflict of interest.

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Integrating science, technology, and experimental knowledge for sustainable innovation: A Living Lab approach to urban biodiversity management

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Abstract

PURPOSE: *This study aims to enhance understanding of STI (Science, Technology, Innovation) and DUI (Doing, Using, Interacting) integration dynamics in sustainable innovation, specifically investigating its role in innovation outcomes, stakeholder engagement, and the institutionalization of sustainable practices in urban lawn management.* ***METHODOLOGY:*** *Using a single case study design, the study captures real-time, dynamic interactions between STI and DUI practices, observing ongoing processes. Data were collected through five focus group interviews with 32 stakeholders, individual interviews, project documentation, and a project diary. Stakeholders included public sector officials, NGOs, private garden owners, and business representatives, each offering insights into policy, environmental practices, and market-driven solutions. The Living Lab methodology, emphasizing co-creation and iterative feedback, guided both data collection and analysis, with NVivo software and manual coding used to identify key themes and challenges in integrating STI and DUI for sustainable innovation.* ***FINDINGS****: The investigation revealed that integrating STI and DUI modes fosters a dynamic synergy: STI provided scientific rigor, while DUI leveraged stakeholder input and local contexts to co-develop adaptive urban biodiversity solutions. This approach addressed location-specific challenges, balancing ecological goals with practical feasibility. For instance, stakeholder engagement refined scientific recommendations, ensuring broader applicability and adoption. Despite tensions between rigor and practicality, the participatory Living Lab methodology facilitated co-creation, aligning scientific insights with real-world needs to enhance sustainable lawn care practices.* ***IMPLICATIONS****: The study contributes to innovation theory by showing how integrating STI and DUI modes fosters socially responsive, adaptable solutions for urban biodiversity management. From a practical standpoint, it underscores the importance of stakeholder engagement in developing tools and strategies that balance scientific insights with practical, real-world application. The project offers a replicable model for integrating formal research with user-driven innovation in sustainability projects.* ***ORIGINALITY AND VALUE:*** *This paper provides a unique contribution by showcasing how the integration of formal scientific research (STI) with practical, user-cantered approaches (DUI) can foster* **innovability**. *The use of the Living Lab methodology to co-create urban biodiversity solutions bridges the gap between academic research and practical application, offering a novel framework for addressing complex environmental challenges through collaborative innovation.*

Keywords: *sustainable innovation, Science, Technology, Innovation, STI, Doing, Using, Interacting, DUI, urban biodiversity, lawn management, Living Lab, stakeholder engagement, participatory innovation, co-creation, climate change adaptation*

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INTRODUCTION

Innovability, the synergy of innovation and sustainability, emerges as a transformative approach to tackling complex global challenges by ensuring that technological advancements are environmentally responsible and socially inclusive (De La Vega Hernández & Barcellos de Paula, 2021). This concept advocates for innovations that move beyond traditional economic growth, instead driving sustainable development by prioritizing environmental integrity and social well-being (Adams et al., 2016). It ensures that technological advancements contribute not only to economic progress but also to long-term ecological sustainability and social benefits (Adams et al., 2016). Despite its potential, the practical realization of innovability remains underexplored, particularly in how different innovation modes can be integrated to achieve sustainable outcomes.

The integration of Science, Technology, and Innovation (STI) with Doing, Using, and Interacting (DUI) modes offers a promising pathway to operationalize innovability. The STI mode emphasizes formal knowledge creation through structured research and development, leading to technological advancements disseminated via products, processes, or services (Jensen et al., 2007; Nunes & Lopes, 2015). In contrast, the DUI mode relies on tacit knowledge and experiential learning, emphasizing practical experience, iterative feedback, and stakeholder engagement (Marzucchi & Montresor, 2017; Jensen et al., 2007). Combining these modes can enhance innovation outcomes by merging structured knowledge with practical adaptability, fostering solutions that are both technologically advanced and responsive to real-world needs (Beynon et al., 2024; Carrillo-Carrillo & Alcalde-Heras, 2021).

However, achieving this integration is complex and fraught with challenges, such as internal conflicts and inefficiencies, especially in contexts where formal research and operational practices are traditionally siloed (Parrilli & Elola, 2012; Marzucchi & Montresor, 2017). Existing studies remain inconclusive on whether STI and DUI modes complement or substitute one another (Najda-Janoszka, 2025). Some argue that combining them enhances innovation, enabling organizations, public institutions, and social communities to benefit from both formal research and practical adaptability (Lundvall et al., 2009; Fitjar & Rodríguez-Pose, 2013). Others underscore the importance of contextual and temporal factors in shaping their combined effectiveness (Beynon et al., 2024). For instance, STI's focus on scientific rigor conceptually complements DUI's emphasis on flexibility, but their practical integration often depends on regional resources and long-term innovation performance outcomes (Beynon et al., 2024; Piercey et al., 2025; Parrilli & Elola, 2012). Research further highlights that the interplay between these modes is influenced by geographic and temporal factors, with peripheral regions favoring DUI-driven approaches and core regions leveraging STI modes for structural innovation performance (Beynon et al., 2024; Piercey et al., 2025). Further, firms pursuing integration of innovation modes face additional risks, such as "over-searching", which generates more ideas than they can absorb, thereby limiting their ability to act effectively (Haus-Reve et al., 2019). Moreover, integrating tacit, experience-based supply-chain knowledge with codified scientific knowledge is highly sector-specific and complicated by differences in innovation speeds and time horizons (Haus-Reve et al., 2019; Beynon et al., 2024; Simms & Frishammar, 2024). These challenges are exacerbated by fundamental knowledge asymmetries, which create communication barriers and a lack of shared understanding between collaborators (Simms & Frishammar, 2024). Ultimately, these insights underscore that achieving innovability through integration of STI and DUI requires nuanced, tailored strategies that account for the socio-economic, sectoral, and spatial dynamics of the target context.

The integration of STI and DUI modes offers a transformative approach to tackling the complexities of urban biodiversity management. As cities expand, the pressures of habitat fragmentation, infrastructure development, and competing land use demands threaten biodiversity, which is vital for ecosystem services such as air purification, temperature regulation, and flood control (Biella et al., 2025; Genovese et al., 2023). These challenges are further complicated by the diverse and often conflicting interests of stakeholders, including government agencies, private entities, NGOs, and local communities (Kopnina et al., 2024). Managing urban biodiversity effectively requires bridging scientific rigor with practical, experience-based solutions, enabling context-specific strategies that address ecological, social, and economic dimensions. Evidence-based practices, such as reduced mowing regimes, exemplify this balance by enhancing biodiversity and mitigating urban heat. However, broader adoption is limited by challenges like public perceptions, operational barriers, and integration into urban planning frameworks (Watson et al., 2020; Biella et al., 2025). These challenges highlight the need for approaches that not only generate knowledge but also ensure its application in real-world contexts.

In this context, the "To Mow or Not to Mow?" project selected as the case study for this research demonstrates how integrating STI and DUI modes can foster innovability in urban biodiversity management. Conducted at Jagiellonian University's Campus Living Lab, the project addresses biodiversity loss caused by conventional lawn-mowing practices,

which often prioritize aesthetic and administrative considerations over ecological benefits (Biella et al., 2025). The Living Lab methodology is scientifically relevant due to its epistemological foundations, which position it as both a tool for knowledge creation and a mechanism for validating that knowledge through real-world application (Verhoef et al., 2019). By combining formal research with community-driven engagement, Living Labs enable iterative co-creation (Stuckrath et al., 2025). This ensures that solutions are grounded in scientific rigor while remaining relevant to stakeholders. In this project, the Living Lab methodology is used to co-create sustainable lawn management practices with a diverse range of stakeholders, including local residents, public authorities, NGOs, and private sector representatives. This participatory approach ensures that solutions are not only ecologically sound but also socially accepted and practically applicable. Local residents provide experiential knowledge about community needs and preferences, public authorities offer regulatory guidance, NGOs contribute environmental expertise, and private sector representatives bring practical, market-driven insights. Through the engagement of these diverse parties, the Living Lab methodology fosters the development of sustainable lawn management practices that are both scientifically rigorous and tailored to the local context (Stuckrath et al., 2025).

The study aims to enhance the understanding of how the integration of STI and DUI modes can foster innovability in sustainable urban biodiversity management. Specifically, it seeks to explore how this integration affects innovation outcomes, stakeholder engagement, and the institutionalization of sustainable practices, with a particular focus on urban lawn management. To achieve this aim, the study has two main objectives: (1) to analyze how the integration of STI and DUI modes enhances innovation outcomes, stakeholder engagement, and the adoption of sustainable practices in urban biodiversity management; and (2) to identify the key tensions and challenges encountered in this integration and propose strategies for addressing them. These objectives are investigated through three research questions (RQs):

RQ1: How can the integration of STI and DUI modes facilitate innovability in urban biodiversity projects?
RQ2: What are the main tensions and challenges encountered in this integration, and how can they be managed?
RQ3: How does stakeholder engagement influence the innovation process and the institutionalization of sustainable practices?

The paper proceeds by first reviewing pertinent literature on innovability and the integration of STI and DUI modes, establishing the theoretical framework for the study. Following this, the methodology outlines the case study approach, data collection methods, and analytical procedures used to investigate the "To Mow or Not to Mow?" project. The findings present the results of the analysis, highlighting the dynamics of integrating innovation modes and their impact on project outcomes. The discussion interprets these findings in light of existing theories, identifying contributions to the literature and implications for practice. Finally, the conclusion summarizes the key insights, addresses limitations, and suggests directions for future research.

LITERATURE REVIEW

The concept of "innovability" bridges innovation and sustainability (De Tomasso & Pinsky, 2022), extending earlier frameworks such as eco-innovation, sustainable business models, and shared value (Pereira et al., 2025; Bocken et al., 2014; Porter & Kramer, 2011). Unlike prior approaches that often emphasized individual dimensions—such as environmental, social, or economic aspects—innovability integrates these pillars into a balanced, systemic framework (De La Vega Hernández & Barcellos de Paula, 2021; Adams et al., 2016). This approach emphasizes co-creating value with diverse stakeholders, while recognizing the environment as an active stakeholder with intrinsic rights (De La Vega Hernández & Barcellos de Paula, 2021; Gilbert et al., 2023).

However, despite its conceptual potential, innovability remains underexplored, particularly in aligning innovation practices with sustainable outcomes. A scoping review in Web of Science found only 15 references explicitly addressing "innovability," with just two empirical studies examining its links to both innovation and sustainability. This limited discourse underscores the need for further research to harmonize innovation processes with sustainability and address the complex challenges of the Anthropocene (Pereira et al., 2025). Recognizing the fragmented and interdisciplinary nature of the existing research – spanning areas such as policy, ethics, and technology management (Cillo et al., 2019) – the scope of the review for this research was expanded to include combinations of related terms such as sustainable innovation, innovation for sustainability, stakeholder engagement, environmental inclusion, and biodiversity. A search using specified terms in titles, abstracts, or keywords in the Web of Science database initially yielded 307 results. The

PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology (Moher et al., 2010) was then applied to identify relevant studies for inclusion, as shown in Figure 1. The search was subsequently refined to remove duplicates, non-English language documents, non-peer-reviewed articles, and studies outside the management field, as the study focuses on managerial perspectives and the integration of innovation and sustainability within organizational contexts. This refinement resulted in 93 entries for consideration.

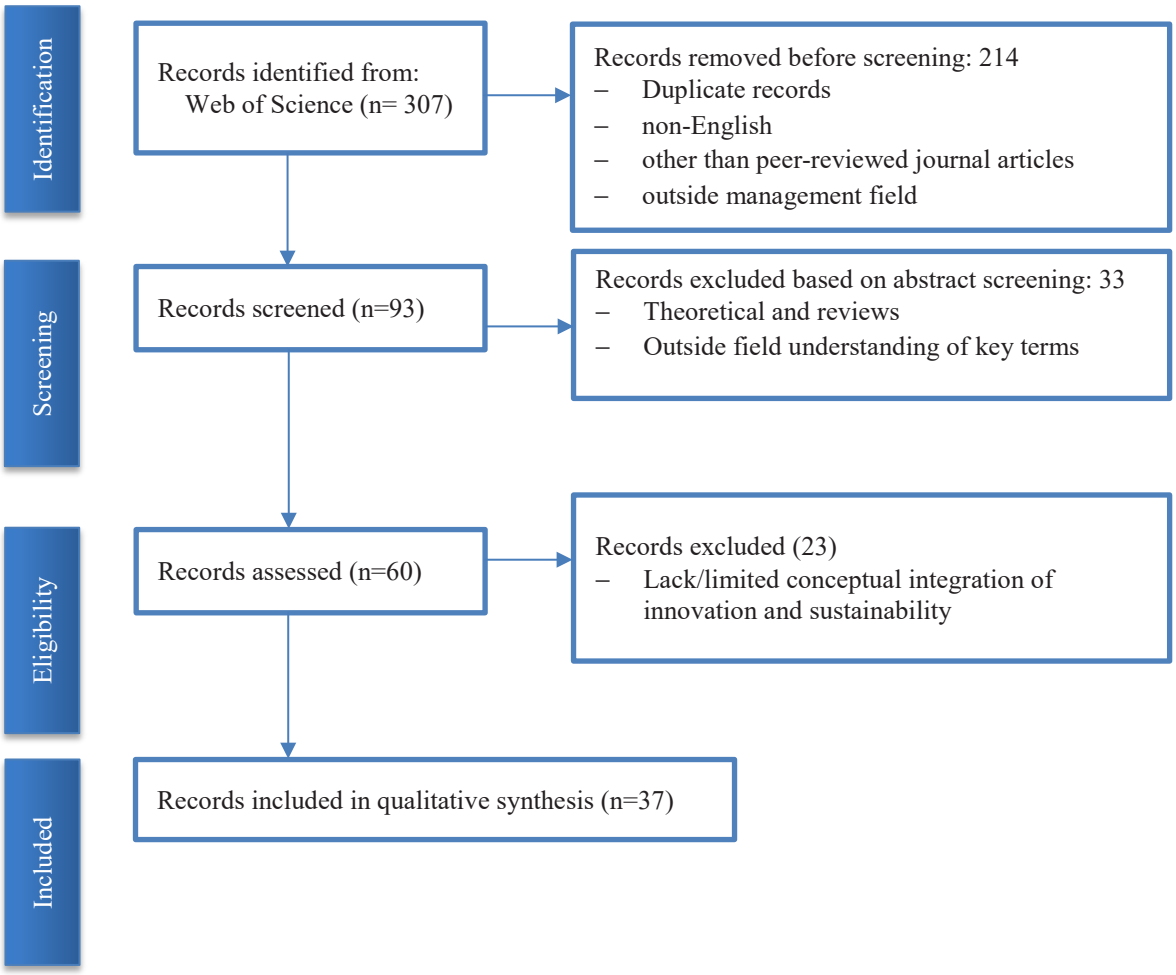

Figure 1. PRISMA flow diagram of performed systematic literature review

During the screening stage, 33 entries were excluded, primarily due to their theoretical or review-based nature, lacking empirical evidence. To focus on original empirical research, we excluded illustrative case studies, systematic reviews, and other non-empirical works to maintain methodological rigor and avoid redundancy. This process resulted in a final sample of 60 articles for eligibility assessment. Following this, a review of the abstracts led to the exclusion of an additional 23 articles. These either referenced sustainable innovation in overly general terms, failing to address the key challenge of innovability—the meaningful integration of innovation and sustainability—or offered only limited insight into the specific dynamics of how these concepts intersect. Others focused solely on selected aspects—economic, social, or environmental. This resulted in a final sample of 37 relevant articles for the qualitative synthesis.

The co-occurrence analysis of keywords resulted in overly distributed, multi-themed outputs with little depth at this stage, likely reflecting the early developmental state of the field. To address this, we conducted a content analysis using thematic analysis.

The thematic analysis of the literature reveals four interconnected themes that address the challenge of integrating innovation and sustainability, encapsulating the economic, social, and environmental dimensions of **innovability.** The first theme, *Stakeholder participation and collaborative practices*, underscores the significance of partnerships and co-

creation in driving sustainability-oriented innovation. Effective collaboration enables diverse stakeholders to align their goals and foster shared solutions, as partnerships bridge gaps in expertise, resources, and priorities. This theme highlights how inclusive frameworks facilitate trust and engagement, while addressing tensions that may arise due to differing organizational logics (Watson et al., 2024; Cambra-Fierro et al., 2023). For example, co-creation between businesses and communities can create shared value by integrating local needs with broader sustainability goals (Goodman et al., 2017).

The second theme, *Context specific nature of sustainability efforts*, highlights that the integration of innovation and sustainability is shaped by the unique socio-economic and ecological conditions of each context, requiring tailored approaches rather than one-size-fits-all solutions. In urban settings, public-private collaborations, such as smart urban projects, demonstrate how technological advancements can address challenges like pollution and citizen well-being by aligning with local needs (Cambra-Fierro et al., 2024). Humanitarian settings, such as refugee camps, highlight the importance of balancing environmental priorities with social needs through operational innovations that improve quality of life under resource constraints (Seifert et al., 2022). Similarly, in agriculture, the adoption of technologies like drip irrigation showcases the necessity of reconciling economic feasibility with environmental goals to meet the realities of farming communities (Greenland et al., 2019).

The third theme, *Scaling sustainable practices and innovation models*, focuses on the systemic expansion of sustainability initiatives, emphasizing the importance of innovative frameworks that enable broader adoption and impact. Scaling sustainability often involves aligning business practices with global frameworks such as the United Nations Sustainable Development Goals (SDGs), as well as utilizing tools like life cycle assessment methodologies to evaluate and enhance environmental performance (Rosati et al., 2023; Goffetti et al., 2023). Dynamic capabilities play a key role, allowing organizations to adapt to shifting societal, regulatory, and market expectations, as seen in industries such as energy and fashion, where sustainability transitions require iterative experimentation and learning (Franzè et al., 2024; Wadin & Bengtsson, 2022). Furthermore, the integration of circular business models, including product-service systems, offers a promising avenue for scaling sustainable practices by decoupling economic growth from resource consumption (Sattari et al., 2022).

Meanwhile, the final theme, *Challenges and barriers to sustainability integration*, addresses the complex obstacles that hinder the effective implementation of sustainability-oriented innovation. Regulatory constraints, conflicting stakeholder priorities, and resource limitations frequently challenge organizations striving to embed sustainability into their operations (Martielli et al., 2024). For instance, small and medium-sized enterprises (SMEs) often face financial and infrastructural barriers that limit their ability to adopt innovative practices, despite their potential for impactful sustainability contributions (Bos-Brouwers, 2010). Stakeholder conflicts further complicate integration, as differing values and objectives between partners can create tensions, particularly in cross-sector collaborations (Stål et al., 2022). Moreover, cultural resistance and lack of institutional support can impede the adoption of sustainable technologies, as illustrated by the slow uptake of water-efficient irrigation systems in agricultural contexts (Greenland et al., 2019).

The insights align with arguments that integrating innovation and sustainability is inherently shaped by the strategic use of diverse forms of knowledge, developed through structured processes and dynamic interactions (Cillo et al., 2019; Pereira et al., 2025). The reviewed literature highlights that various forms of knowledge – including structured frameworks and formalized methodologies spanning scientific research and industrial R&D, as well as context-specific practices and experiential insights from stakeholder interactions – are essential for guiding innovation toward sustainable outcomes (Alcalde-Heras & Carrillo-Carrillo, 2024; Marzucchi & Montresor, 2017; Rosati et al., 2023). These dynamics illustrate that sustainable innovation emerges from the interplay of diverse informational inputs and their application in specific contexts (Greenland et al., 2019; Goodman et al., 2017). This interplay is particularly important in addressing environmental impacts at both production and consumption levels, where solutions must integrate technological rigor with local adaptability to achieve meaningful outcomes (Alcalde-Heras & Carrillo-Carrillo, 2024).

This dynamics aligns closely with two distinct modes of innovation: Science and Technology-based Innovation (STI) and Doing, Using, and Interacting (DUI) (Jensen et al., 2007; Najda-Janoszka, 2025). The STI mode reflects the structured, systematic processes that underpin technological advancements, codified knowledge, and breakthrough innovations, primarily driven by academic, corporate, or governmental research and development (Jensen et al., 2007; Alcalde-Heras & Carrillo-Carrillo, 2024). In contrast, the DUI mode emphasizes the value of tacit knowledge and experiential learning, derived from iterative, context-specific feedback and stakeholder interactions (Marzucchi & Montresor, 2017; Parrilli & Heras, 2016). While STI fosters transformative, research-driven innovation, DUI thrives on adaptability, enabling incremental, user-centred improvements that are often critical in addressing specific local or environmental challenges

(Thomä, 2017; Goodman et al., 2017). Studies suggest that integrating STI and DUI modes can significantly enhance innovation outcomes by combining the strengths of both approaches (Beynon et al., 2024; Alhusen & Bennat, 2021). By merging formal scientific research with practical experiential learning, organizations can create innovations that are not only technologically advanced but also highly relevant to market needs and adaptable to real-world conditions (González-Pernía et al., 2015; Carrillo-Carrillo & Alcalde-Heras, 2021). This integration bridges the gap between theoretical knowledge and practical application, fostering an environment that supports continuous improvement and adaptive learning (Isaksen & Nilsson, 2013; Marzucchi & Montresor, 2017).

However, integrating STI and DUI modes is complex and highly context-dependent, shaped by regional, sectoral, and temporal factors. STI's emphasis on scientific rigor and codified knowledge contrasts with DUI's focus on tacit, experiential learning, making their integration conceptually complementary but practically challenging (Najda-Janoszka, 2025; Piercey et al., 2025). For example, peripheral regions often rely on DUI due to resource constraints and the local nature of experiential knowledge, while metropolitan regions are better positioned to leverage STI for structural innovation, benefiting from access to advanced R&D infrastructure and skilled labor (Beynon et al., 2024; Piercey et al., 2025). These disparities highlight the need for context-sensitive strategies that align with regional capabilities and innovation goals. Sectoral dynamics further amplify the challenges of STI-DUI integration. In industries where innovation speeds and time horizons differ, integrating tacit supply-chain knowledge with STI's codified research often results in misaligned objectives and coordination difficulties (Haus-Reve et al., 2019; Simms & Frishammar, 2024). For instance, high-tech and low-tech firm collaborations face challenges in bridging knowledge gaps, coordinating efforts, and aligning objectives (Simms & Frishammar, 2024). These tensions are further exacerbated as firms often struggle to balance the volume of external inputs with their capacity to process and utilize ideas effectively, resulting in inefficiencies and fragmented innovation efforts (Haus-Reve et al., 2019). Additional coordination difficulties arise when attempting to align STI's codified, structured knowledge with DUI's tacit, experience-based insights, which can lead to misaligned objectives or redundant activities (Simms & Frishammar, 2024). Partnerships can further complicate matters by causing strategic misdirection, where firms prioritize technically intriguing ideas that fail to address operational or market priorities (Beynon et al., 2024). These challenges underscore the importance of robust knowledge management systems to facilitate communication, align expectations, and establish shared frameworks for collaboration (Simms & Frishammar, 2024). Additionally, adopting an ambidextrous approach (Zakrzewska-Bielawska, 2021) can help balance STI's exploratory potential with DUI's practical adaptability, allowing firms to address immediate challenges while progressing toward long-term sustainability goals (Raisch & Birkinshaw, 2008; Cillo et al., 2019).

Despite these challenges, the integration of STI and DUI modes presents a promising framework for addressing critical sustainability issues, particularly in urban contexts. However, theoretical frameworks addressing the dynamics of STI and DUI integration remain underdeveloped, especially in relation to urban sustainability challenges, where the complementary roles of both modes could foster adaptable and rigorous innovations. This gap is particularly notable in the domain of biodiversity, which often remains an implicit rather than explicit focus in sustainability-oriented innovation efforts, even though it is critical for maintaining ecosystem services (Cambra-Fierro et al., 2024; Greenland et al., 2019). While studies frequently address related concerns such as environmental performance, urban pollution, and resource management, targeted approaches to directly address biodiversity loss and ecosystem degradation remain limited. This gap highlights the potential of STI and DUI integration to tackle the complexities of urban biodiversity management, which requires balancing ecological preservation with the pressures of urban development (Mainwaring et al., 2024). Urban biodiversity management seeks to maintain and enhance biodiversity within cities increasingly threatened by human activity, infrastructure expansion, and habitat fragmentation (Biella et al., 2025). As cities grow, these pressures intensify, creating a dynamic tension between the need for biodiverse green spaces and competing land-use demands (Kopnina et al., 2024). This challenge extends beyond environmental integrity, encompassing deeply interwoven social and economic dimensions (Mainwaring et al., 2024). Biodiversity loss undermines essential ecosystem services, such as air purification, temperature regulation, and flood control, directly impacting urban populations (Genovese et al., 2023). Therefore, finding sustainable, innovative approaches to preserve urban nature is crucial for societal well-being and the functioning of urban ecosystems (Bruno et al., 2024).

Managing urban biodiversity effectively, however, is inherently complex and requires a context-specific approach that addresses the diverse social, economic, and environmental challenges cities face. Urban biodiversity initiatives must navigate the varied interests of stakeholders, including government agencies, private entities, NGOs, local communities, and environmental organizations, each of which brings distinct priorities and levels of engagement (Biella et al., 2025; Kopnina

et al., 2024). A key challenge lies in reconciling ecological preservation with aesthetic and functional needs, as exemplified by lawn mowing practices (Sehrt et al., 2020). Frequent mowing, motivated by concerns such as aesthetics, administrative costs, and tick prevention, limits biodiversity by favoring a narrow range of species (Ignatieva & Hedblom, 2018; Watson et al., 2020). Conversely, less frequent mowing, or a "low-intensity regime," fosters greater plant diversity, supports small organisms, reduces overheating, and mitigates the urban heat island effect (Biella et al., 2025; Watson et al., 2020). Despite evidence that reducing mowing frequency enhances biodiversity and reduces administrative costs (Watson et al., 2020), its large-scale adoption remains constrained by gaps in understanding how to implement these practices effectively, public perceptions, and integration into urban planning frameworks. Bridging scientific rigor with practical, stakeholder-driven approaches appears crucial for overcoming these barriers. Integrating structured STI knowledge with DUI methods may enable practical, adaptable strategies, fostering sustainable urban biodiversity solutions.

Integrating STI and DUI modes and fostering innovability requires frameworks that enable their convergence in practical settings. **Living Labs** provide a collaborative platform for integrating structured research (STI) with experiential learning (DUI) to address sustainability challenges. Drawing on theories of open innovation, participatory design, and systems thinking, Living Labs engage researchers, businesses, public authorities, and communities in co-creating, testing, and refining solutions (Schuurman et al., 2016; Nyborg et al., 2023). By merging ecological, technological, and social insights through participatory methods such as workshops and iterative feedback, they bridge theoretical knowledge with practical application, fostering interdisciplinarity and transdisciplinarity (Fam et al., 2020).

Building on this concept, **Campus Living Labs** transform universities into innovation hubs, engaging students, faculty, and stakeholders to tackle real-world issues such as biodiversity loss and sustainable urban development (Evans et al., 2015; Fam et al., 2020). These labs integrate STI's structured research methods, such as experiments and data analysis, with DUI's adaptive, stakeholder-driven practices to ensure solutions are scientifically robust and socially relevant (Nyborg et al., 2024; McCrory et al., 2022). Inter- and transdisciplinary collaboration is central to this process, drawing on natural sciences for ecological insights, engineering for technological solutions, and social sciences for stakeholder engagement and societal dynamics. Participatory methods align these contributions toward shared goals, while embedding problem-solving into education helps participants develop technical skills, systems thinking, and collaborative capabilities (Nyborg et al., 2024; Verhoef et al., 2019). By integrating systems thinking and participatory methodologies, Campus Living Labs exemplify the potential for interdisciplinary collaboration and scalable solutions to complex sustainability challenges (Nyborg et al., 2024; Fam et al., 2020). However, despite their promise, empirical studies documenting how STI and DUI modes interact within these frameworks remain scarce, highlighting a need to explore how participatory processes shape sustainable innovation outcomes

In summary, integrating STI and DUI modes through frameworks like Living Labs – particularly Campus Living Labs – presents a promising opportunity to address the complexities of urban biodiversity and sustainability challenges. While promising, this approach raises critical questions for further exploration: (1) How can this integration facilitate innovability in urban biodiversity projects? (2) What tensions and challenges arise, and how can they be addressed? (3) How does stakeholder engagement influence innovation and institutionalization of sustainable practices? These questions aim to uncover strategies for optimizing STI-DUI integration, addressing tensions, and enhancing stakeholder engagement to institutionalize sustainable practices.

METHODOLOGY

Research design (contextualization)

This study employs a single case study design to explore the integration of STI (Science, Technology, and Innovation) and DUI (Doing, Using, and Interacting) modes within the "To Mow or Not to Mow?" project at Jagiellonian University. Single case studies are particularly suited for investigating complex, contemporary phenomena in their real-world contexts, where detailed, contextual understanding is essential (Yin, 2017; Flyvbjerg, 2006). This approach facilitates an in-depth examination of the specific dynamics between STI and DUI, capturing nuanced insights that broader research designs often overlook (Ridder, 2017). The "To Mow or Not to Mow?" project, with its dual focus on biodiversity and sustainability, serves as a bounded unit of analysis, providing a rich context for studying how structured scientific methods intersect with participatory, user-driven processes.

The selection of this project as the unit of analysis is deliberate (Yin, 2017), reflecting its relevance to urban biodiversity challenges such as habitat degradation, species loss, and climate adaptation. A systematic review conducted as part of this research revealed a significant gap in empirical studies addressing urban biodiversity issues, particularly urban lawn management, from a perspective that incorporates stakeholder participation and input. The project addresses this gap directly by offering a unique opportunity to explore how formal, research-based knowledge (STI) interacts with stakeholder-driven, experiential knowledge (DUI) to co-create adaptive and socially responsive solutions. Furthermore, its reliance on the Living Lab methodology, emphasizing iterative feedback and stakeholder engagement, provides a valuable lens for examining the integration of diverse knowledge systems to address environmental challenges effectively. Finally, an ongoing study was chosen over a retrospective analysis to capture the project's real-time evolution, enabling a deeper understanding of how iterative feedback, stakeholder engagement, and adaptive decision-making unfold in practice.

Although single case studies are sometimes critiqued for limited generalizability, their strength lies in offering granular insights that inform broader theoretical frameworks (Yin, 2017; Takahashi & Araujo, 2019). To address this limitation, this study employs analytic generalization, ensuring that findings contribute to understanding STI-DUI integration across similar sustainability initiatives (Flyvbjerg, 2006). The exploratory approach prioritizes uncovering patterns, mechanisms, and challenges, particularly in contexts where existing theory offers limited guidance (Takahashi & Araujo, 2019; Ridder, 2017; Najda-Janoszka & Daba-Buzoianu, 2018). Methodological triangulation further strengthens validity by enabling cross-verification and capturing diverse perspectives (Yin, 2017). Additionally, the participatory nature of the project, involving stakeholders such as public authorities, NGOs, private residents, and businesses, enhances the findings' applicability to broader contexts.

By situating this study within a bounded, context-rich environment, the research provides both theoretical advancements and practical contributions. While it offers insights specific to urban lawn management, its findings extend to broader discussions on integrating STI and DUI modes in urban sustainability projects. This study establishes a replicable framework for similar initiatives, offering transferable lessons for fostering co-created, sustainability-oriented innovations in diverse settings.

Data collection

Triangulation is employed in the case study research to ensure the validity and reliability of findings, utilizing multiple methods to gather comprehensive data (Najda-Janoszka & Daba-Buzoianu, 2018). These methods include interviews (using focus and semi-structured individual techniques), desk research (using structured file review and document retrieval from internal sources) and journaling (using a technique of open-ended reflective journaling) (Table 1).

To capture diverse perspectives, between January and June 2024, five focus group interviews were conducted with stakeholder groups and project participants. These sessions provided collective insights into the challenges of integration and the practicalities of project implementation. Subsequently, in July and August 2024, two semi-structured individual interviews were conducted with faculty authorities and the principal investigator of the pilot project. These interviews aimed to gather in-depth, personal reflections on the project's conditions, experiences, and outcomes. To minimize retrospective bias and provide a more dynamic understanding of the project's development, the journaling method was applied (Olorunfemi, 2024). The principal investigator of the analyzed project maintained a project diary between January and July 2024, documenting the project's progress alongside personal reflections and observations. These qualitative insights were further enriched with data from project documentation spanning September 2023 to June 2024. This documentation, systematically collected as the project was prepared and executed, provided a broader organizational context and a detailed timeline of the project's development, complementing the perceptions and observations gathered through other methods.

Table 1. Gathered material

Method	Technique	Instrument	Description	Number of documents/ interviews	Number of transcribed, written pages
Interview	Semi-structured focus group interview	Scenario-based guide	Public sector (F1) – 12 participants, NGO (F2) – 10 participants, residents (F3) – 7 participants, private sector (F4) – 3 participants, pilot project principal and co-investigators (F5) – 11 participants Duration: 51min – 121min Timeframe: January – June 2024	5	185
Interview	Semi-structured individual interview	Scenario-based guide	Pilot project principal investigator (I1), faculty authority (I2) Duration: 31min – 70min Timeframe: July, August 2024	2	45
Desk research	Structured file review and document retrieval from internal sources	Document review protocol and catalogue	Project Proposal (PP), Project Timeline (PT), CLL Competition Rules (CLL), Protocols from Living Lab competition committee (PCLL), Flagship Project: 2023 Report (Rep1), Flagship Project: Report for the first half of 2024 (Rep2) Timeframe: September 2023 – July 2024	8	76
Journaling	Open-ended reflective journaling	Project diary	Pilot Project Manager's Log (PPML) Timeframe: January – July 2024	1	8

Data analysis

The **method** of qualitative content analysis was employed to provide a comprehensive understanding of the STI and DUI integration process. This method uses a systematic **approach** to extract rich, detailed insights from narrative data, capturing nuanced perspectives and experiences related to integration challenges, project implementation, and organizational conditions (Schreier, 2012). Within this method, the **technique** of thematic coding and categorization was applied to organize and analyze the data systematically.

The data – comprising transcripts of interviews, project documentation, and the project diary – was initially processed using NVivo software. This tool was employed for its advanced capabilities in managing large datasets and efficiently organizing coding frameworks (Paulus et al., 2014). NVivo facilitated the development of the initial coding structure, enabling the identification of key themes. However, the process was further thoroughly refined manually, allowing for a more nuanced interpretation and cross-validation of the results. This iterative combination of software-supported and traditional manual coding ensured a comprehensive and reliable analysis (Najda-Janoszka & Daba-Buzoianu, 2018; Maher et al., 2018).

The thematic coding and categorization procedure was applied across three levels of analysis: individual perspective, project implementation level, and organizational conditions. This combined approach ensures a comprehensive understanding of the integration process, from identifying challenges and evaluating strategies to examining institutional influences on project success. In our analysis, we applied theory-driven codes derived from innovation management literature on STI and DUI, and emerging codes that were inductively developed from the data where new patterns and themes emerged during the coding process**.** A systematic, iterative consensus process was undertaken by three researchers to ensure reliability. To comprehensively analyse themes and gain a deeper understanding of the various facets of STI and DUI integration, it was crucial to divide them into distinct sub-themes. The following table presents an organized overview of these sub-themes, detailing key categories, corresponding codes, and illustrative sample quotes that highlight their relevance (Table 2).

Table 2. Coding procedure

Theory driven codes			
Main category	**Codes**	**Source**	**Sample quotes**
STI	Research and Development (R&D); research; scientific methods; technological advancements; formal knowledge; technical expertise; patents; lab experiments; evidence-based; data-driven	Jensen et al. (2007); Nunes & Lopes (2015); Beynon et al. (2024); Alhusen & Bennat (2021); Isaksen & Karlsen, (2010)	However, the university does have authority. And the knowledge that comes from scientific research is strong. People do follow it, after all (...) (F3_P3)
DUI	Practical application; experiential learning; user feedback; collaboration; hands-on; iterative process; community involvement; stakeholder interaction; fieldwork; problem-solving	Jensen et al. (2007); Nunes & Lopes (2015); Beynon et al. (2024); Alhusen & Bennat (2021); Isaksen & Karlsen, (2010)	Yes, this experience accumulates year by year, each year teaches us something... and we also make decision-making mistakes, but we learn from them and try to correct them moving forward (F1_P4).
Emerging codes			
Main theme	**Second order codes**	**First order codes**	**Sample quotes**
Integration Process of DUI and STI Modes *How STI and DUI modes come together through collaboration and co-creation, while navigating the challenges of their integration within sustainability projects*	Collaborative Synergy	Combining scientific research with practical, user-centred insights Combining interdisciplinary insights to address sustainability challenges Living lab methodology	Well, it certainly leads to the exchange of experiences and potential cooperation, not only from the perspective of our project but also regarding other issues in general (…) (I1)
	Innovation Tensions	Balancing scientific rigor with practical, user-driven needs Managing cross-disciplinary and cross-sectoral priorities	The humanities part has no problem with this, (...) so it's kind of their natural environment, whereas the 'exact sciences' have a big problem with it; they don't understand it at all (...) (I1)
Sustainability-Driven Innovation (Innovability) *How integrated innovation modes produce tangible outcomes in sustainability, including environmental, technological, and social impacts*	Environmental and social responsibility	Addressing biodiversity and climate challenges through innovation Engaging local communities in sustainability efforts	It was also an exchange of experiences so that we could get feedback from these people afterward—whether it worked, whether it was successful, what observations they had—whether it worked at all or didn't, or whether it required modifications. Whether it works in all conditions, and so on and so forth, to get them a bit more involved in the topic, to shift their attention away from commercial things (I1)
	Technological and Social Solutions	Developing user-centred, practical tools (e.g., web applications) Living lab methodology	In my research, I've always aimed and strived to create utilitarian tools that can be used by society, rather than doing research just for the sake of research. The goal is to create tools for protection, tools for action, for building a better reality. So, this methodology or strategy is a perfect fit, a bullseye, in that regard. (I1)
Stakeholder engagement *How stakeholders shape innovation through their involvement, collaboration, and the challenges of integrating diverse actors into the process*	Stakeholder roles	Contribution of public institutions, NGOs, and local communities Sharing responsibility and decision-making in co-creation processes	But there are also different expectations from the residents, as the gentleman here mentioned, and even within a single building, there are already expectations. On a city-wide scale, everyone has their own opinion about mowing; we all consider ourselves experts on the subject. So, in addition to the dilemma of whether to mow or not, we also face the challenge of how to explain that the fact we are mowing is actually a good thing. (F1_P4)
	Collaboration dynamics	Building trust and fostering open communication among stakeholders Ensuring long-term stakeholder commitment and engagement	It will be difficult to really maintain the interest of these people, or simply to keep this target engaged, so that they get involved in these activities, are interested, and truly want to educate themselves (I1)

Emerging codes			
Main theme	**Second order codes**	**First order codes**	**Sample quotes**
Project management dynamics *How organizational aspects facilitate the effective integration of DUI and STI modes by ensuring coordination, support, and the resolution of practical barriers*	Project coordination	Aligning interdisciplinary teams and incorporating stakeholder input Adapting project timelines to accommodate real-world constraints Managing evolving stakeholder expectations and project needs	The extreme unpredictability of the weather is going to drive me crazy. This year, I can't plan anything. It was supposed to be dry – the sky is overcast and it's windy like before a storm, and then a moment later, there's unbearable heat...(…) And finally, there are some positive effects and more butterflies (PPML)
	Institutional support and challenges	Administrative and financial support for interdisciplinary projects Managing time, resource and administrative barriers	I am glad that we have real support; we wouldn't be able to manage without it. I am worried that the procedures might drag on for a long time. What we need most of all is a detailed specification, which we can't create without focus group research. I feel immense pressure and how little time there is for everything (PPML)
Social impact and knowledge transfer *How the project's outcomes translate into broader societal impact through public education, knowledge-sharing, and the institutionalization of practices for long-term sustainability*	Public education and outreach	Raising public awareness on biodiversity, climate issues and sustainability practices Translating scientific findings into actionable knowledge for non-experts	(…) I don't believe that we will be able to do something like that, that we will... suddenly stop mowing lawns, right? And I think we need to find some kind of compromise here (…) (F2_P2)
	Institutionalising innovation	Creating frameworks for continuous collaboration (beyond the project's duration) Establishing long-term knowledge-sharing mechanisms	I would like to strengthen this (...) there will be an appointee responsible for external collaboration. We are supposed to establish a council for cooperation. We are going to invite a few people to join. We will try to get certain things moving, and that will be her task, to get this cooperation going. (…) And I think these will also be projects that will have a more implementation-oriented character. Meaning, the University wants to open up to various collaborations and institutionalize this somehow. But if I had to tell you in three straightforward words how I see it? Right now, I'm at the stage where the more projects that bring benefits to researchers and students, the better, simply put (I2)

Validity and reliability

To ensure the rigor and trustworthiness of the study, multiple validation strategies were applied, aligning with qualitative research standards (Lincoln & Guba, 1985; Najda-Janoszka, 2016). Credibility was enhanced through methodological triangulation. The use of multiple methods, techniques and data sources allowed for cross-verification of findings, reducing the risk of bias and increasing the robustness of interpretations. Dependability was ensured through researcher triangulation, with three researchers independently conducting coding and validating emerging themes. NVivo software facilitated initial coding, while manual verification provided deeper contextual interpretation, improving analytical rigor. Confirmability was addressed by implementing a transparent and systematic data analysis process. To mitigate potential researcher bias—particularly given the involvement of the principal investigator (PI) as a co-author—two additional researchers, not directly affiliated with the PI, independently reviewed and validated the findings. The study adhered to a structured protocol for data collection, coding, and thematic development, ensuring that interpretations were grounded in the data rather than researcher preconceptions. Finally, analytic generalization (Yin, 2017) strengthened transferability, ensuring that insights from this case study contribute to broader discussions on STI-DUI integration in sustainability projects. By providing detailed contextual analysis and a replicable framework, the study offers findings relevant beyond its immediate case. These measures enhance the validity and reliability of the research, reinforcing its contribution to innovation and sustainability studies.

FINDINGS

The findings begin with a detailed presentation of the *To Mow or Not to Mow?* project, establishing it as the unit of analysis and situating it within Jagiellonian University's Campus Living Lab. This section outlines the project's objectives, methodology, and the specific challenges it addresses, particularly in sustainable urban lawn management. Following this overview, the analysis builds on themes identified through the coding and categorization process (Table 2), examining the integration of DUI and STI knowledge modes, stakeholder engagement dynamics, and the project's broader social impact.

The outline of the case chosen – "To Mow or Not to Mow?" project

The "To Mow or Not to Mow?" project, launched in 2023 as part of Jagiellonian University's Campus Living Lab (CaLiLab), seeks to promote sustainable urban biodiversity management by exploring how different lawn mowing frequencies impact ecosystems. As urbanization intensifies, creating urban heat islands and reducing biodiversity (Mainwaring et al., 2024), traditional landscaping practices such as frequent mowing are becoming increasingly unsustainable. This project challenges those practices and aims to identify biodiversity-friendly alternatives for urban green space management (Biella et al., 2025; Watson et al., 2020). The urgency of such initiatives is underscored by global biodiversity crises, with evidence suggesting we are already experiencing the sixth mass extinction driven by human activities (Barnosky et al., 2011; Tollefson, 2019).

Frequent mowing is often valued for its aesthetic appeal but restricts plant species from flowering, limiting biodiversity (Biella et al., 2025). Additionally, intensively mowed lawns are less resilient to heat and drought, often leading to dead patches that require frequent watering, fertilization, and herbicide application. These interventions generate noise, dust, and greenhouse gases, contributing to further environmental degradation (Watson et al., 2020). Recent research demonstrates that reducing mowing frequency can increase plant species diversity by up to 30%, thereby providing more food sources and shelter for pollinators, which are essential for healthier urban ecosystems (Sehrt et al., 2020).

The "To Mow or Not to Mow?" project's primary goal is to develop scientifically backed recommendations on lawn management practices that optimize biodiversity while meeting the aesthetic and functional needs of urban residents. Another major objective is the development of a web-based application to guide users in making informed decisions about sustainable lawn care (PP). This application will integrate scientific data and stakeholder feedback to create a practical tool that balances environmental benefits with everyday lawn management needs. The experimental phase of the project includes 64 plots with varying mowing frequencies, ranging from one to eight cuts per year, as well as plots mowed only once every two years (PP). Over the course of three growing seasons, the study assesses a range of environmental parameters, including microhabitat conditions, soil fauna activity, soil bacterial and fungal diversity, soil respiration rates, above-ground biodiversity, mycorrhizal development, tick exposure, and the risk of invasive species encroachment (PP). This comprehensive analysis will provide key insights into how different mowing practices affect urban ecosystems.

A critical feature of the "To Mow or Not to Mow?" project is its participatory approach, facilitated by CaLiLab. Launched in spring 2023 at Jagiellonian University, this innovation platform supports collaborative research and the co-creation of solutions through funding, training, and mentoring (CLL). By engaging a diverse range of stakeholders—including academia, businesses, public authorities, and community members—CaLiLab fosters the development of practical, real-world solutions to environmental challenges. Within the Living Lab framework, the Jagiellonian University campus serves as a microcosm of wider society, providing a controlled environment for experimenting with and refining innovative ideas (Stuckrath et al., 2025; Martek et al., 2022). The CaLiLab approach to participatory research follows a quintuple helix model, incorporating the natural environment as a legitimate stakeholder, which further enriches the co-creation process (Rep. 1; Rep. 2). Interdisciplinary and participatory approaches are not only encouraged but also supported and expected in funded projects (PCLL). Depending on the project's initial design, these aspects can be expanded and deepened during execution, with merit-based support provided by CaLiLab (PCLL).

The "To Mow or Not to Mow?" project has been structured into several phases in alignment with the CaLiLab approach (PP; PT). The initial test phase in 2023 involved pilot studies on the Jagiellonian University campus to assess the basic impacts of mowing frequency on biodiversity. This phase can be characterized as scientific experimentation within the framework of formal knowledge creation through structured research (STI). Based on the results obtained, the full project was developed and, in December 2023, was selected for formal financial support from CaLiLab. Since then, the project has benefited from ongoing training, mentoring, and substantive guidance provided by the platform. The expanded version of the project broadened its research scope to include inter and transdisciplinary collaboration with deeper stakeholder engagement. The scientific team was extended to include geographers, social communication experts, and management scientists, while stakeholder participation increased with the involvement of public sector officials, non-governmental organizations, private garden owners, and business representatives. As a result, the STI approach was combined with multi-stakeholder engagement, iterative feedback, and tacit knowledge transfer—key characteristics of the DUI mode. In 2024, the actual participatory activities were implemented, marking the integration process of the two innovation modes. By the end of 2025, the project aims to produce comprehensive recommendations on optimal mowing practices and launch a web application that will provide data-driven guidance for sustainable lawn management. Ongoing

collaboration with stakeholders and the incorporation of their input will shape both the project's recommendations and the design of the web-based application, ensuring it meets the diverse needs of urban stakeholders.

The current study focuses on this second phase (December 2023 – August 2024), specifically examining the process of integrating the two innovation modes.

Thematic analysis of key findings

The analysis unfolds in three key areas, guided by the themes identified through the coding and categorization process and aligned with the study's three research questions (Table 2). First, it examines the integration of DUI and STI knowledge modes, exploring their synergy, tensions, and how they shape the project within the broader concept of innovability. Next, it investigates stakeholder engagement, focusing on participant roles, shared responsibilities, and project management dynamics. Finally, the analysis turns to the project's social impact, highlighting its role in public education on biodiversity and climate issues while outlining frameworks for fostering ongoing collaboration.

Integrating STI and DUI for innovability – synergies and tensions

The data gathered across focus and individual interviews, project documentation, project diary, reveals that both STI and DUI modes are simultaneously present and actively used in the 'To Mow or Not to Mow?' project. The STI mode is evident in the project's reliance on formal research methods and scientific inquiry (PP), as it conducts '*complex, multi-area experimental research*' that is '*unique due to the large number of factors studied and the broad, diverse area covered.*' (I1) This reflects a structured, data-driven approach to innovation, characteristic of the STI mode. On the other hand, the DUI mode emerges through the active involvement of external stakeholders in the innovation process (PP). The project invites people from outside academia to contribute their perspectives, a practice rarely seen in traditional science: '*We invite people from outside to give their input, we listen to their voices... and we consider their feedback in creating our recommendations.*' (I1).

The documentation confirms that the project design is clearly based on the integration of STI and DUI modes (PP; PCLL). Its goal is not only to conduct in-depth research but also to develop user-centered tools, including a web application, through a participatory research process. These tools serve as part of the project's technological and social solutions to standardize sustainable mowing practices (PP). Protocols from the CaLiLab competition committee (PCLL) indicate compliance with the Living Lab's participatory approach by combining scientific rigor with community engagement, ensuring that solutions are shaped by both data and stakeholder experiences. Importantly, an interview with faculty authorities signals institutional commitment to supporting this research direction, with explicit interest in expanding opportunities for academic engagement and enhancing researchers' competencies: *"[It] facilitates a different way of employee activity" and allows researchers to "go outside" and test ideas before scaling them up"* (I2). This perspective extends beyond merely combining disciplinary expertise within research teams toward a **transdisciplinary approach**, where disciplines merge beyond their boundaries and integrate non-academic (societal) knowledge from practitioners, policymakers, and communities.

The integration of STI and DUI modes in the project fosters transdisciplinary synergy by bringing together biologists (including botanists, zoologists, and environmentalists), geographers, communication experts, and management scientists. Rather than simply combining distinct disciplinary perspectives, methods, and knowledge, the project design assumed a merging of expertise, with researchers working closely together toward a common, real-world solution that is both scientifically rigorous and practically applicable (PP). The selection of project team members was based on their ability to contribute their specialized expertise while also engaging in deep collaboration across disciplines (I1). While the biology and geography teams led the experimental research, they acknowledged the need for expertise in stakeholder communication and engagement, which led to the inclusion of social science researchers. Their role was not limited to supporting outreach efforts but was integral to the project's co-creation process, ensuring that scientific findings translated effectively into actionable, stakeholder-driven solutions (I1). Similarly, cross-sectoral synergy was recognized as crucial for the project's success, with input from various stakeholders, including public sector representatives, NGOs, and the local community, ensuring that the developed solutions are both ecologically sustainable and socially accepted:

> *'It would be very useful now if the city commissioned such monitoring studies every year to assess our chances of getting infected by ticks, to show that not every tick is dangerous' (F2_P3)*

While the project was designed to integrate diverse expertise through a transdisciplinary approach, its execution revealed tensions and challenges in practice, as documented in interviews and the project journal (PPML). Aligning and managing the diverse contributions within the project proved difficult, particularly due to ontological and epistemological differences between disciplines. As noted, *'the humanities have no problem with this, (...) it's their natural environment, whereas the exact sciences struggle with it; they don't understand it at all'* (I1). These challenges were further compounded by the differing perspectives and practices among stakeholders from various sectors. For example, allotment garden owners often form a tight-knit community with a clear understanding of gardening, emphasizing control over nature through frequent mowing and the removal of unwanted plants and animals. This perception extends to garden managers and housing cooperatives, who also struggle to grasp the importance of biodiversity and the benefits of less intensive lawn care. Some participants expressed anthropocentric views, driven by fear and personal priorities, seeing biodiversity as a threat:

> *'But there are also different expectations from residents, as you mentioned, and even at the level of a single block, there are already expectations. On the scale of the whole city, everyone has their own opinion about mowing; we all think we know about it' (F1_P4)*

Tensions also emerge in balancing scientific objectives with stakeholder expectations. Scientists find it difficult to accept non-scientific arguments, which intensifies the conflict and generates internal resistance. Disagreements arise between the goals of biologists and the practical needs of stakeholders. While there is hope for a tool to unify these practices, scepticism remains: *'The question is, will there be any willingness to use something like this?'* (F4_P2). This highlights the challenge of reaching a compromise that respects both scientific recommendations and public input, underscoring the need for ongoing dialogue throughout the project to ensure flexible and adaptive approaches. The Living Lab methodology provides a suitable framework and toolbox to facilitate this process, yet its effectiveness is constrained by the fact that CaLiLab itself is still in an emergent phase. As a developing initiative, it is still refining its mechanisms for long-term stakeholder engagement, structured collaboration, and interdisciplinary integration (Rep1; Rep2).

Stakeholder engagement and project dynamics

Stakeholder engagement in the "To Mow or Not to Mow?" project is a dynamic and evolving process aimed at addressing the challenges of integrating STI and DUI modes. The strategy focuses on continually involving new stakeholders, expanding the network, and articulating emerging expectations. Key moments of collaboration – touchpoints – were identified, where stakeholders from different sectors were brought together to address specific problems and achieve project milestones. Participation took various forms, ranging from focus interviews and the construction of ecological installations on campus to nature walks that encouraged more open and interactive exchanges (Rep.1; Rep.2). These touchpoints are critical as they act as enabling constraints, with new insights often bringing new tensions:

> *'It was about connecting different disciplines... And then it turned out that A[…] saw an area of contact, although for me it was initially completely unclear' (I2).*

Engagement is managed through negotiation and mediation, aiming to make stakeholders feel they are organically contributing to the project's direction: "*I don't want to impose anything. I would prefer that people are convinced they came up with it themselves*' (I1). It helps in building trust and fostering open communication among diverse stakeholders, which is essential for overcoming tensions and aligning goals. Despite this inclusive approach, the temporary nature of the project presents a barrier to sustained engagement, with some stakeholders expressing concern over whether the collaboration will continue beyond the project's duration: '*The downside is that... when the grant or project ends, the forum ends too. There's no guarantee it will survive*' (F3_P6). This highlights the need for longer-term strategies to maintain stakeholder involvement and ensure the project's sustainability.

The management of the project required a high level of coordination and flexibility. The first eight months were particularly intense, with activities ranging from field experiments to engaging with the socio-economic environment. A key challenge in project management was dealing with the unpredictability of weather, which necessitated frequent adjustments to the project's detailed schedule. This unpredictability had a significant impact on the organization of the project team and the well-being of its members, '*the enormous unpredictability of the weather wears me down nervously*' (PPML).

Executing the project in line with the living lab methodology added another layer of complexity. Researchers were required to step out of their traditional roles and engage with stakeholders, necessitating the development of new skills and competencies. This transition was challenging for many team members who were accustomed to strictly scientific tasks:

> *'it is extremely difficult because here we have many strictly scientific tasks and many soft ones. So, for me, it's something completely new, as it combines two types of projects' (I1).*

The 24-month timeframe allotted for the project's completion further intensified these challenges, as the team had to balance experimental research, stakeholder engagement, and the development of web applications, all while managing communication and promotional activities – '*the deadlines are very demotivating... we don't have enough time*' (I1).

Institutional support was crucial in advancing the project. The interdisciplinary team, comprising nearly twenty researchers, Ph.D. students, and students from various fields, was brought together through extensive academic experience and networking. However, the project faced challenges such as complex administrative procedures and inadequate compensation for staff, which impeded full engagement. Despite these obstacles, CaLiLab succeeded in fostering a collaborative, trust-based ecosystem—'*The path seems much more pleasant... Thanks to the people who work here and are genuinely friendly, creating an amazing atmosphere of good work*' (I1). This support included access to CaLiLab's network, expert guidance, and an expanding array of training resources (PPML). Nevertheless, CaLiLab, as an emerging entity, faces challenges in developing tools for effective stakeholder engagement and building long-term relationships (Rep.1; Rep.2). A significant limitation within the quintuple helix model is the structure of innovation projects themselves, often seen outside the university as rigid, short-term, and goal-oriented. This perception can hinder long-term collaboration and trust with external stakeholders.

Social impact and institutionalization of practices

The "To Mow or Not to Mow?" project has made a significant social impact by engaging in public education and outreach to raise awareness about biodiversity, climate change, and sustainable practices. The research highlights the deeply rooted "lawn-mowing culture," where frequent mowing is not just a routine but an expression of control and personal aesthetics. One participant remarked, '*I don't believe we'll be able to suddenly stop mowing lawns. I think we need to find a compromise here*' (F2_P2). The project goes beyond merely informing the public, it actively seeks to transform ingrained social attitudes through hands-on engagement, such as wildflower meadow planting workshops (Rep. 2). Through public outreach, it also challenges the long-standing norm of frequent mowing, which many view as a symbol of control over nature, *'Mowing is more than a habit; it's part of a culture where controlling nature is viewed as necessary'* (F2_P2). It achieves this through direct interaction, such as hands-on activities like wildflower meadow planting workshops (Rep. 2). By addressing habitual behaviors, the project responds to global climate challenges while enhancing the university's reputation as a leader in social innovation. This recognition has placed additional pressure on the project team to deliver impactful outcomes, as one member noted: '*Our pilot project suddenly became a flagship project for the department in the context of mitigation of climate change and biodiversity loss... which is flattering, but it also brings a burden*' (I1).

Institutionalizing innovation is a core objective of the project, which employs the Living Lab methodology to create frameworks for ongoing collaboration and long-term knowledge-sharing. It serves as a model for integrating academic research with practical community engagement, involving a broad spectrum of stakeholders – from the public to socio-economic entities – to develop practical tools and strategies for real-world challenges. Stakeholder involvement has been critical at every stage, from research to the co-creation of a web-based application. This co-creation process, as one participant highlighted, is innovative because '*we invite outsiders to give their feedback, which we then use to develop our recommendations. This rarely happens in science*' (I1).

Importantly, the project's impact has been reinforced by strong institutional support. The Living Lab approach has received pronounced commitment not only from the Faculty but also from the central authorities of the university, demonstrating a broader institutional investment in participatory, transdisciplinary research (I2; Rep.1; Rep.2). This support enhances the potential for scaling such initiatives beyond a single project, embedding them into the university's long-term research and engagement strategies. The project's social impact extends beyond its immediate environmental goals, further establishing the university as a leader in social innovation. By facilitating public dialogue on biodiversity and engaging diverse community members, the initiative has sparked broader conversations about the role of urban spaces in addressing global climate challenges. This heightened visibility has placed added pressure on the project team to

deliver long-term, meaningful outcomes. However, it has also emphasized the need to continue fostering innovation and collaboration even after the project concludes.

Despite challenges – such as the project's temporary nature and the difficulty of maintaining stakeholder engagement over time– it represents a crucial step toward embedding participatory, science-based practices in urban biodiversity management. By fostering a sense of shared responsibility and collaboration, the project has laid the groundwork for long-term institutionalization. The development of a web-based application further ensures that these efforts remain accessible and actionable, helping users make informed decisions about lawn care while balancing ecological and socio-economic considerations. Through these initiatives, *To Mow or Not to Mow?* not only bridges the gap between academic research and community-driven action but also contributes to lasting cultural and institutional change in sustainable urban green space management.

DISCUSSION

The "To Mow or Not to Mow?" project exemplifies a balanced integration of STI (Science, Technology, and Innovation) and DUI (Doing, Using, and Interacting) modes for biodiversity and climate challenges. However, the broader academic landscape still lacks sufficient research that systematically embeds stakeholder participation in biodiversity innovation (Biella et al., 2025; Boiral & Heras-Saizarbitoria, 2017). Most biodiversity studies continue to emphasize scientific advancements without fully integrating social dimensions or stakeholder engagement (Biella et al., 2025). This gap is problematic, as sustainability transitions require not only technical solutions but also inclusive, participatory approaches that ensure long-term viability and acceptance of conservation measures (Boiral & Heras-Saizarbitoria, 2017).

Although STI-based approaches provide essential technical and scientific foundations, they frequently operate in isolation from the social realities and knowledge systems of local communities, policymakers, and practitioners. The neglect of co-creative, DUI-based methodologies results in rigid solutions that may lack adaptability to diverse ecological and socio-economic contexts (Lécuyer et al., 2024). Research institutions often prioritize expert-driven models (Jensen et al., 2007), side-lining experiential learning, and interactive innovation that could enhance the relevance and uptake of biodiversity strategies. Moreover, although co-creation in innovation has been widely discussed in business and technological fields (Ramaswamy & Gouillart, 2010; Najda-Janoszka & Sawczuk, 2022), its application to biodiversity remains underexplored. There are few empirical studies on how stakeholder participation directly influences biodiversity innovation beyond consultative roles (Lécuyer et al., 2024). Theoretical frameworks acknowledge the importance of integrating local knowledge (Stuckrath et al., 2025), but practical implementations remain sparse, particularly in higher education and research-driven sustainability projects.

Theoretically, combining STI's formal research with DUI's experiential learning can enhance innovation outcomes by merging structured knowledge creation with practical adaptability (Jensen et al., 2007; Najda-Janoszka, 2024). However, the project's findings revealed significant tensions that arise and multiply during the integration of these modes throughout project implementation. This supports existing research that highlights the challenges of integration, indicating that efforts to combine STI and DUI often lead to conflicts and inefficiencies (Haus-Reve et al., 2019; Alcalde-Heras & Carrillo-Carrillo, 2024; Marzucchi & Montresor, 2017). These challenges are especially evident in university settings, where formal research and operational practices often exist in silos, within single disciplines. This limited interdisciplinary collaboration bounds the potential for transdisciplinary solutions needed for complex, real-world problems (Fam et al., 2020; Stuckrath et al., 2025). Research in academia is usually guided by rigid disciplinary norms, prioritizing depth over breadth, which can hinder the integration of diverse knowledge bases (Fam et al., 2020; Perkmann & Walsh, 2009). In the investigated project, tensions at the ontological and epistemological levels emerged right from the start. There were significant differences in how participating academics from different disciplines understood key constructs such as "experiment," "lab," or "engagement" (F5). As the project progressed, differing perspectives on research priorities became apparent, leading to ongoing discussions about the direction and focus of subsequent tasks. These discussions intensified as various outcomes were expected, highlighting the challenge of aligning diverse academic viewpoints within a single project framework (PPML, I1).

Furthermore, the divide between research and practical application reinforces the siloed approach commonly observed at universities (Perkmann & Walsh, 2009; Fam et al., 2020). Formal research typically focuses on theoretical rigor and academic publication, while operational practices involving external stakeholders prioritize flexibility and immediate problem-solving. This pragmatic approach can sometimes conflict with the structured nature of academic research (Parrilli

& Heras, 2016). In the investigated project, aligning these two modes proved complex. Researchers struggled to shift from their traditional scientific roles to becoming facilitators of stakeholder engagement, a shift that required new skills and greater adaptability (Evans et al., 2015; Grunwald et al., 2024). Thomä (2017) highlights that incorporating DUI elements into STI-focused projects often necessitates a significant cultural shift within research teams (Grunwald et al., 2024).

In this project, some participants struggled with the concept of early stakeholder involvement, as they were accustomed to engaging stakeholders only in the final stages. This underscored the need for developing consensus within teams on how to balance scientific research with addressing socio-economic needs and expectations (Alcalde-Heras & Carrillo-Carrillo, 2024; Stål et al., 2022). Achieving this balance had a direct impact on the distribution of responsibilities, task division, and risk-sharing, making it a crucial factor for project success. To address these challenges, the project adopted a strategy of gradually evolving its network by expanding stakeholder circles, creating new relationships, and articulating emerging expectations. This began with the formation of a multidisciplinary team, followed by the incorporation of the CaLiLab's hybrid model of STI and DUI, and culminated in the inclusion of socio-economic stakeholders, which ultimately aligned the project with the Lab's hybrid strategy (Schuurman et al., 2016; Almirall & Wareham, 2008).

The project's use of the Living Lab methodology aimed to address these tensions by encouraging co-creation and iterative feedback between researchers and stakeholders (Schuurman et al., 2016). This approach significantly improved the recognition and understanding of stakeholder needs and provided a diverse informational foundation for the perspectives and expectations presented. As a result, it deepened the understanding of the project's complexity and highlighting its broader environmental and social impact (Mulgan, 2019). However, the CaLiLab itself is still in an emerging phase and is developing its tools for long-term stakeholder engagement. Moreover, administrative procedures and insufficient compensation highlight systemic barriers that undermine effective project execution (Isaksen & Nilsson, 2013; Grunwald et al., 2024). Constrained by university-level procedures and STI-based expectations, CaLiLab's support is currently limited to the structure of typical grant-funded research projects, which are often bound by stringent timelines. This structure has proven insufficient for addressing the complexities of inter and transdisciplinary collaboration, field experiments, and ongoing stakeholder engagement. For instance, the team expressed frustration over tight deadlines and the need to submit follow-up funding applications before fully evaluating the project outcomes (I1). Furthermore, the project's temporary nature poses a significant limitation, undermining efforts to build lasting trust with stakeholders and to sustain the developed innovations beyond the funding cycle (Bocken et al., 2019; Evans et al., 2015).

Despite challenges, the project's approach to knowledge transfer and social impact is significant. It utilized insights from stakeholders throughout the research process, technical innovation design, and supportive activities. Recognizing, aligning, and discussing these inputs took extensive effort, addressing concerns, distrust, misperceptions, and misinformation. This work was invaluable for developing sustainability-driven innovation at the university with environmental and social impact. However, it was time-consuming, requiring learning, new skills, and institutional support, which itself had to adapt. The integration of scientific findings into user-centred tools, like a web application, shows how STI and DUI can converge to produce actionable knowledge (Verhoef et al., 2019). Projects that blend formal research with practical application are better positioned to influence societal attitudes and behaviors toward sustainability (Alcalde-Heras & Carrillo-Carrillo, 2024; Caniglia et al., 2017). However, the project's reliance on temporary frameworks raises questions about its ability to establish lasting change, highlighting a gap between the literature's ideal of continuous improvement and the practical realities of project-based innovation (Brinkhurst et al., 2011).

Integrating STI and DUI for urban biodiversity innovation

The integration of STI and DUI modes in the "To Mow or Not to Mow?" project was essential for fostering innovability—the capacity to create sustainable, socially responsible innovations. By combining the structured, data-driven approach of STI with the practical, user-focused insights of DUI, the project developed effective solutions for urban biodiversity management. This approach addressed both ecological and societal challenges associated with over-mowing, encouraging a shift away from conventional "mowing culture" toward more sustainable practices that enhance biodiversity. The Living Lab methodology facilitated continuous feedback between researchers and stakeholders, ensuring that the solutions were relevant, adaptable, and accessible to the community. This synergy exemplifies how blending formal scientific knowledge with experiential learning can drive innovations that are not only technologically sound but also aligned with the evolving needs of diverse stakeholders.

Moreover, the project's participatory approach strengthened community engagement and knowledge transfer. By involving local residents, NGOs, and public institutions, the project translated scientific findings into actionable

strategies. The co-creation process empowered stakeholders, ensuring that the project's outcomes were both scientifically valid and socially accepted. This integration of social and technological innovation demonstrates how urban biodiversity initiatives can leverage both STI and DUI modes to promote long-term sustainability and behavioral change in urban green space management.

Proposition 1: The **integration of STI and DUI modes** in sustainability projects **increases the diversity of knowledge inputs**, leading to more innovative and resilient biodiversity management solutions.

New insights on university engagement and biodiversity

In the broader context, the academic community at Jagiellonian University shows strong support for biodiversity conservation, driven by two key factors. First, younger generations, including students, are acutely aware of the urgency for environmental protection, the consequences of climate change, and the necessity for proactive ecological actions. Second, the actual implementation of environmental protection policies, particularly on biodiversity and climate, is largely influenced by decision-makers at national, European, and global levels. However, local authorities are crucial for executing these policies effectively at a regional or municipal level. Jagiellonian University, as one of Poland's premier research institutions, is in a unique position to become a leader in advocating for these actions. It can initiate and promote measures rooted in rigorous scientific research, while also being open to the experiences and knowledge of stakeholders outside the academic sphere.

This combination of STI and DUI approaches aligns with the university's third mission—engaging with society and fostering collaboration with socio-economic entities. By merging academic insights with stakeholder-driven perspectives, the university can play a pivotal role in driving both theoretical and practical innovation. Achieving this balance, however, requires ongoing interdisciplinary collaboration and the recognition of external knowledge sources as equally valuable to traditional academic expertise.

Proposition 2: Universities that adopt a **dual STI-DUI engagement strategy** (scientific rigor + stakeholder co-creation) will have a **greater impact on biodiversity policy implementation** at the municipal level than those relying solely on traditional academic research dissemination.

Addressing the tensions in integrating STI and DUI

The integration of STI and DUI modes is an evolving process rather than a ready-made framework for immediate implementation. As the *To Mow or Not to Mow?* project demonstrated, this process exposed tensions across ontological, epistemological, practical, and organizational dimensions. Natural scientists prioritized scientific rigor, while social scientists emphasized stakeholder engagement, leading to divergent research priorities. External stakeholders also held conflicting views on biodiversity management, creating friction between scientific recommendations and public preferences. These tensions were actively managed through a flexible stakeholder network and continuous dialogue, but this required time, effort, and openness to new contributions, placing additional demands on the project team.

The case of Jagiellonian University highlights the key role academic institutions can play in shaping biodiversity policies and fostering inter- and transdisciplinary collaboration. However, this approach requires navigating inherent tensions in knowledge production. Some participants initially struggled with the need for early stakeholder involvement, as engagement is often limited to the final stages of research. This underscores the importance of clear communication and structured collaboration to align scientific research with socio-economic and environmental needs. Achieving this balance influences how responsibilities are allocated, tasks are structured, and risks are managed throughout the project.

Proposition 3: The level of **epistemological and organizational tensions** in transdisciplinary research projects **decreases when stakeholder engagement is structured in progressive phases**, rather than introduced as a single-stage process.

Practical and organizational challenges in integrating STI and DUI

Tensions arose from the strict timelines imposed by funding cycles, which conflicted with the iterative, adaptive nature of stakeholder-driven innovation. The project's temporary nature heightened stress for both researchers and stakeholders, as tight deadlines limited the flexibility needed for meaningful engagement. Researchers also faced the challenge of developing new skills in inter- and transdisciplinary collaboration and stakeholder management, yet this demand was not matched by adequate financial compensation. Administrative barriers, such as rigid institutional procedures, further

complicated project execution. While phased stakeholder engagement and iterative management helped mitigate some issues, institutional rigidity, financial constraints, and the project's temporary framework remain unresolved, restricting the full potential of STI and DUI integration.

These challenges highlight the need for institutions like Jagiellonian University to reform administrative procedures and establish better financial compensation structures for projects requiring inter- and transdisciplinary expertise. Greater flexibility in project timelines, sustained engagement, and iterative stakeholder feedback are crucial for ensuring long-term success in STI-DUI integration. Additionally, ongoing efforts are needed to build researchers' capacity to engage in hybrid projects, equipping them not only with technical research skills but also with expertise in stakeholder collaboration.

Proposition 4: The **long-term sustainability and effectiveness of transdisciplinary projects** integrating STI and DUI depend on **institutional flexibility in project management**, particularly in adapting funding structures, administrative processes, and **stakeholder engagement mechanisms** to support iterative and co-creative approaches.

CONCLUSION

The findings from this study contribute to the ongoing theoretical debate on the relationship between STI and DUI modes of innovation, where some argue for their complementarity and others see them as substitutive. This research supports the complementarity view, showing that when integrated effectively, STI and DUI modes can mutually reinforce each other. In the "To Mow or Not to Mow?" project, the structured, data-driven knowledge of STI was enriched by the practical, stakeholder-driven insights of DUI, leading to more socially responsive and adaptive innovations in urban biodiversity management. This underscores the potential of hybrid innovation models to address complex challenges requiring both scientific rigor and practical flexibility, moving beyond the notion that these modes must remain distinct or competitive.

Moreover, the study advances the discussion on the dynamic interplay between these two modes by demonstrating how iterative stakeholder engagement—core to DUI—can enrich and reshape the scientific agenda set by STI. In this case, the inclusion of diverse non-academic perspectives did not dilute scientific rigor but enhanced the relevance and applicability of solutions, offering a practical demonstration of how both modes can operate synergistically. This finding suggests that under the right conditions, STI and DUI are not only compatible but can drive more impactful, sustainable innovations when combined effectively. The study also provides insights into managing the tensions that arise from integrating these modes, a challenge often overlooked in theoretical discussions.

From a practical standpoint, the project highlights the importance of flexible and adaptive project management approaches that allow for ongoing stakeholder input and iterative refinement of solutions. Organizations aiming to implement hybrid STI-DUI innovations must invest in capacity-building, ensuring that researchers possess both technical expertise and the skills needed for inter and transdisciplinary collaboration and stakeholder engagement. Furthermore, institutions should seek to reform rigid administrative procedures and improve financial compensation structures to better support projects requiring diverse skill sets and adaptive processes. Finally, this study underscores the necessity of sustained engagement and co-creation to secure long-term societal acceptance and successful implementation of innovations in biodiversity management.

Although the study provides valuable insights, it has certain limitations. Its reliance on a single case study focused on urban biodiversity management within a university setting may limit the generalizability of its findings. The context-specific approach may not fully capture the broader challenges of integrating STI and DUI modes across different sectors or regions. Additionally, the study's time-bound nature limited the ability to assess the long-term effects of these integrations, particularly in terms of sustained stakeholder engagement and the durability of outcomes beyond the project's funding cycle.

To build on these findings, extended studies are needed to explore the long-term societal impacts of combining STI and DUI modes, particularly in fostering ongoing community engagement. Further research into institutional barriers to inter and transdisciplinary collaboration could provide insights into developing more flexible organizational structures that better support innovability. Expanding the research into other sectors, such as private initiatives or diverse geographical regions, would offer a comparative understanding of how the balance between STI and DUI modes can be optimized across different innovation ecosystems.

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The authors declare no conflict of interest.

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The role of green blue ocean strategy in enhancing frugal innovation through IoT and AI: A resource-based view perspective

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Abstract

***PURPOSE**: This study explores the role of Green Blue Ocean Strategy (GBOS) in promoting frugal innovation by leveraging IoT and AI from an RBV theoretical perspective, targeting creative entrepreneurs in Central Java, Indonesia. **METHODOLOGY**: A quantitative approach was used, with Structural Equation Modelling (SEM) analyzed via AMOS. Data from 262 creative entrepreneurs were collected through an online closed questionnaire using purposive sampling. **FINDINGS**: The study reveals that (1) IoT does not significantly impact frugal innovation, (2) AI positively influences frugal innovation, and (3) GBOS effectively mediates the relationship between IoT, AI, and frugal innovation, suggesting that integrating sustainable strategies with technology can lead to more cost-effective and inclusive innovations. **IMPLICATIONS** for theory and practice: The study extends the RBV framework by integrating the GBOS concept, demonstrating its effectiveness in optimizing digital technology for sustainability-driven innovation. It contributes to the literature on sustainability strategies and the Resource-Based View by introducing a novel theoretical model that links GBOS, IoT, and AI with frugal innovation. Practically, GBOS offers a pathway for creative entrepreneurs to overcome resource constraints and achieve competitive advantages through sustainable practices. **ORIGINALITY AND VALUE**: This study introduces Green Blue Ocean Strategy (GBOS) as a novel conceptual framework that extends the traditional Blue Ocean Strategy (BOS) by integrating sustainability principles. GBOS addresses both economic and environmental concerns, enabling businesses to achieve cost-effective innovation. Grounded in the Resource-Based View (RBV), this study systematically develops and empirically tests GBOS by linking it with IoT, AI, and frugal innovation. The framework offers a new lens for sustainable competitive advantage in resource-constrained environments.*

***Keywords:** internet of things, artificial intelligence, green blue ocean strategy, frugal innovation, resource-based view, sustainability, sustainable strategy, digital technology, sustainability-driven innovation, sustainable innovation*

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INTRODUCTION

Organizations need to prioritize innovation to achieve high levels of commercial and financial success (Donkor et al., 2018; Farida & Setiawan, 2022; Hameed et al., 2021). Nevertheless, some organizations lack the technological capabilities to gain a competitive advantage, primarily due to limitations in financial resources and knowledge. Other limitations that must be considered include the inability to embrace digital values (Panjaitan et al., 2023), the level of knowledge quality (Moonti et al., 2023), the absence of intellectual flexibility, and the complexity of technological advancements (Panjaitan et al., 2021; Vermesan et al., 2022) the absence of intellectual flexibility, and the complexity of technological advancements (Hiong et al., 2020; Panjaitan et al., 2022). To tackle these challenges, organizations must utilize the Internet of Things (IoT) and Artificial Intelligence (AI) to maximize the efficiency of their limited resources. By incorporating technology and AI, companies can encourage cost-effective innovation (Qin, 2024), decrease operational expenses (Calabrese et al., 2023; Nawaz et al., 2024), improve their ability to adapt to market fluctuations (Sullivan & Wamba, 2024) and minimize risks related to market unpredictability (Grimaldi et al., 2023). This study aims to investigate how the Green Blue Ocean Strategy (GBOS) mediates the relationship between IoT, AI, and frugal innovation, offering actionable insights for leveraging these technologies to drive cost-efficient, sustainable innovations in resource-constrained environments.

Integrating IoT and AI enhances frugal innovation by optimizing resource use and generating commercial value, particularly in creative sectors operating with limited resources (Huang et al., 2022). This study explores innovative strategies to optimize resource use and enhance cost efficiency while maintaining product quality. This study emphasizes the importance of cost-efficient innovations that streamline essential features, maintain product quality, and minimize expenses while generating value. Artificial Intelligence (AI) and the Internet of Things (IoT) play a crucial role in developing marketing strategies by creating shared consumer value and aligning with the aims of frugal innovation (Lee & Lee, 2015; Wu & Monfort, 2023). Although there have been disruptive technology improvements, the Internet of Things (IoT) can enhance company performance and facilitate effective consumer interactions (Lo & Campos, 2018). The study addresses the following research questions (RQs):

RQ1: How can the Green Blue Ocean Strategy (GBOS) leverage IoT and AI to drive frugal innovation?
RQ2: What are the strategic implications of integrating sustainability-driven strategies with digital technologies to enhance cost efficiency?

Past research emphasizes the increasing significance of technology adoption among those involved in business activities. Qin (2024) states that integrating IoT and AI infrastructure enables cost-effective innovation in less developed countries, resulting in sustainable and fair growth. In addition, AI technology improves services and boosts user satisfaction (Ghaith et al., 2023). IoT and AI working together enhance digital marketing decisions (Jia et al., 2021) and can predict how customers will act, like when airlines repurpose services. Additional research suggests that AI can assist organizations in digital marketing by generating advertising content, decreasing acquisition expenses, enhancing customer happiness, attracting potential employees, and broadening target demographics (Van Esch & Stewart Black, 2021). Nevertheless, there is a lack of understanding regarding business strategies that effectively utilize environmentally friendly technology, like the Internet of Things (IoT) and Artificial Intelligence (AI), sustainably. In aiming to achieve low-cost innovation using IoT and AI applications, this gap encourages academics to investigate perspectives rooted in RBV theory to synthesize the Blue Ocean Strategy (BOS) (Iruthayasamy & Iruthayasamy, 2021) and Green Innovation Process (GIP) concepts (M. Wang et al., 2021; Xie et al., 2019). This research extends the Blue Ocean Strategy framework by integrating sustainability considerations, offering a pathway for leveraging digital technologies such as IoT and AI for cost-effective and environmentally conscious innovation. This study explores strategic frameworks that enable firms to harness IoT and AI for sustainable innovation, focusing on cost-efficiency and environmental sustainability in resource-constrained contexts.

The path from environmentally friendly process innovation to economic performance is not as important as understanding the concept of the green innovation process from environmentally friendly technology innovation, which highlights the fundamental difference between ecologically friendly product innovation (Mingyue Wang et al., 2021). In other words, boosting technological innovation provides room for creativity in the business's eco-friendly operations, promoting the development of eco-friendly products. Meanwhile, Kim & Mauborgne (2017) presented the BOS concept, which highlights a strategy to steer clear of markets that are already saturated with competitors, or the "Red Ocean," by focusing on providing distinctive goods or services where businesses can create new demand and eliminate the relevance

of competitors. Consequently, there remains a theoretical and practical knowledge gap that prevents the development of a new perspective, known as GBOS, based on these two principles. To the best of our knowledge, the concept of Green Blue Ocean Strategy (GBOS) has not been explicitly established in prior literature. While studies on Blue Economy (Ni et al., 2024; Soma et al., 2018) and Green Ocean Strategy (Markopoulos & Ramonda, 2022) discuss sustainability-driven business models, none integrate these approaches into a unified framework that addresses cost efficiency, environmental sustainability, and digital transformation. This study introduces GBOS as a novel strategic framework that extends Blue Ocean Strategy by embedding sustainability into market innovation, GBOS provides firms with a strategic pathway to simultaneously address ecological and economic challenges. The concept of GBOS integrates sustainability into the Blue Ocean Strategy, aiming to create new market opportunities that are both cost-effective and environmentally sustainable (Barbosa et al., 2019). The objective is to achieve corporate growth, simultaneously produce ecological and economic value, and lessen adverse environmental effects. Therefore, the novelty of the GBOS idea aligns with the RBV theory's perspective, offering firms the potential to deliver unique talents and competencies to create sustainable excellence.

GBOS is conceptualized by integrating key principles from Blue Ocean Strategy (Kim & Mauborgne, 2004), sustainability-driven innovation (Xie et al., 2019), and the Resource-Based View (Barney, 1991). This study develops GBOS through a structured approach: (1) identifying gaps in Blue Economy and Green Innovation frameworks, (2) synthesizing core elements of cost-efficiency and environmental sustainability, and (3) empirically validating GBOS using Structural Equation Modeling (SEM) with data from creative entrepreneurs in Indonesia. By focusing on creating affordable and resource-efficient goods and services while considering the innovation's effects on the environment and society, the application of GBOS as a mediator can enhance the value of frugal innovations in the context described in this article. This strategy aligns with RBV because it leverages the business's unique ability to incorporate environmental considerations into innovation plans to generate a competitive advantage (Barney, 1991; Barney et al., 2001; Teece et al., 1997). Moreover, incorporating GBOS into frugal innovation can stimulate cost-effective, sustainable, and inclusive solutions that address broader market demands while considering environmental sustainability. This may open the door to developing a more comprehensive RBV theory, where resources are considered in terms of their effects on society and the environment, as well as their economic and competitive value (Tate & Bals, 2016). Therefore, using GBOS as a mediator in frugal innovation can be a profound innovation that extends RBV theory's application to include sustainability and social responsibility as crucial components of competitive advantage. This approach is also grounded in RBV theory, which focuses on utilizing internal resources and capabilities to achieve a competitive advantage. This suggests that our understanding of sources of competitive advantage is evolving, with social and environmental added value now seen as a component of what makes resources valuable and difficult for rivals to imitate (Gibson et al., 2021).

The researchers' study examines the ability of the Internet of Things (IoT) and Artificial Intelligence (AI) to provide consumer value and cost efficiency. The paper references the works of (Gellweiler & Krishnamurthi, 2020; Gupta & Maheshwari, 2024; Rath et al., 2024). Furthermore, there have been additional studies conducted on BOS, as documented by Dzingirai et al. (2023), Hossain et al. (2024), Vasiljeva et al. (2019), and Yunus and Sijabat (2021). While GBOS introduces a novel conceptual framework by integrating BOS and sustainability-driven innovation, its empirical validation is crucial to refine its theoretical foundations and practical applications. Future studies should explore its mediation role in linking IoT, AI, and frugal innovation across diverse industries, particularly in resource-constrained settings. There are limitations to research that combines the RBV perspective, IoT, and AI through the role of GBOS. This research conceptually separates IoT and AI to explore the role of each technology in frugal innovation. IoT is used for automatic and real-time data collection, while AI focuses on data analysis to generate cost-effective, data-driven decisions (Baccour et al., 2022; Raparthy & Dodda, 2023).

This separation allows the study to investigate how IoT can facilitate innovation by enhancing real-time data collection and how AI can maximize efficiency in operational processes through data analysis. The rationale behind this separation is that AI relies on data gathered by IoT to analyze innovation processes. In the context of frugal innovation, IoT simplifies data collection from various production or distribution points with minimal costs, while AI processes this data to provide strategic, cost-saving recommendations in essence, IoT provides data, and AI generates solutions from that data. Furthermore, respondents' competencies, specifically creative entrepreneurs in Central Java, indicate a sufficient understanding of both IoT and AI technologies and their implications for sustainable business strategies (Baccour et al., 2022). Ultimately, the integrated use of these technologies drives cost-efficient innovation. This study aims to explore the role of GBOS in leveraging IoT and AI to drive frugal innovation, focusing on creative entrepreneurship in resource-constrained contexts. Thus, this study extensively examines the role of GBOS in addressing the evolving nature of creative

endeavors that prioritize environmentally sustainable technology to consistently generate cost-effective innovations. The goal is to achieve company expansion by creating ecological and economic value while minimizing environmental impact. The uniqueness of GBOS aligns with the Resource-Based View (RBV) paradigm, emphasizing the ability of companies to utilize their resources to attain long-lasting superiority. The introduction should establish the context of the research, demonstrating its relevance and importance. It should clearly state the research aim, questions, and identify gaps in the existing literature. The introduction must also define key terms and outline the manuscript's structure and objectives.

LITERATURE REVIEW

Resource-Based View (RBV)

According to the Resource-Based View (RBV) approach, a company's resources and capabilities are valuable for maximizing opportunities and mitigating environmental concerns. For instance, prominent corporations can decrease expenses to fulfill their products' requirements (Barney, 1995) The Resource-Based View (RBV) emphasizes that a firm's internal resources and unique capabilities are critical in sustaining a competitive advantage, particularly in rapidly evolving markets (Barney, 1991). However, RBV alone may not fully capture the dynamic nature of technological innovation, especially when considering the integration of AI and IoT. To address this gap, incorporating the Dynamic Capabilities (DC) framework, which focuses on the firm's ability to adapt, reconfigure, and leverage its resources in response to environmental changes, can provide a more robust theoretical grounding for this study (Singh et al., 2019). The Resource-Based View (RBV) highlights the importance of internal resources and unique capabilities as critical drivers of competitive advantage (Barney, 1991). However, given the dynamic and rapidly changing nature of technological innovation, particularly with the integration of IoT and AI, the Dynamic Capabilities (DC) framework is essential to complement RBV.

DC emphasizes the firm's ability to adapt, reconfigure, and leverage its resources in response to market changes, thereby offering a more robust foundation for understanding innovation and competitive advantage in volatile markets. This illustrates the possibility of foreseeing rival risks arising from a company's valued internal resources and competencies. The blue ocean strategy (BOS) aims to generate value and establish new markets by leveraging the company's untapped internal capabilities, thereby circumventing saturated (red ocean) and fiercely competitive markets (Kim & Mauborgne, 2017). Nevertheless, the BOS concept should prioritize the consideration of external resources in the formulation of business plans that are both cost-effective and environmentally sustainable. As a result, companies need to combine environmental management with the core idea of maintaining a competitive edge at the corporate level (Barney, 1986). Moreover, digital services enable enterprises to establish precise entry barriers and develop isolation mechanisms to preserve their competitive advantages in product offerings (Barney & Clark, 2007; Sánchez-Montesinos et al., 2018). Based on the RBV viewpoint, this study argues that a company can stay ahead of the competition over the long term by using a strategy that other companies cannot easily replicate (Barney, 1991).

Internet of Things (IoT) and Artificial Intelligence (AI)

Increased frugal innovation is significantly influenced by the Internet of Things (IoT) (Park et al., 2022). The Internet of Things (IoT) and Artificial Intelligence (AI) are interdependent technologies that drive innovation by leveraging large datasets for real-time analytics (Sasikumar et al., 2022). AI's capabilities in data analysis and automation are enhanced by the extensive data collection enabled by IoT devices, creating a synergistic relationship that drives both operational efficiency and sustainable innovation (Baccour et al., 2022; Zhang et al., 2020). Creatively utilizing available resources can facilitate frugal innovation by surpassing fundamental resource limitations, resulting in more economical and practical solutions (Quan et al., 2019). Organizations can develop creative processes that maximize productivity with minimal resources by utilizing IoT technology and a bricolage approach. While IoT provides the infrastructure for data collection, AI utilizes these data streams to optimize decision-making processes. IoT serves as the data collection backbone, enabling real-time monitoring of resources and processes, while AI processes these data streams to derive actionable insights. This synergistic relationship is critical for implementing the GBOS framework, as it allows businesses to make informed decisions that balance cost-efficiency with sustainability goals (Baccour et al., 2022; Patil & Gokhale, 2022). For instance, AI's predictive analytics optimize IoT-generated data, driving frugal innovation by minimizing resource waste and enhancing operational efficiency.

This integration is essential for implementing the GBOS framework, where real-time data insights drive sustainable value creation. This allows them to address the needs of various populations at a reasonable cost. Frugal innovation employs cost-saving strategies, such as leveraging inexpensive labor, and involves reconfiguring products and processes to minimize expenses, maximize energy efficiency, and improve overall effectiveness (Juhro & Aulia, 2019). When resources are limited, as they often are for low-income groups, frugal ideas can thrive, demonstrating that these solutions are both flexible and affordable (Santiago et al., 2019). The Internet of Things (IoT) is widely acknowledged as a crucial technology propelling innovation trends, especially in environmental monitoring (Scilimati et al., 2017). The integration of IoT and AI technologies is crucial for enabling real-time data analytics, which drives strategic decision-making and operational efficiency (Jankovic & Curovic, 2023). While IoT provides the data infrastructure, AI leverages these data streams to optimize resource allocation and enhance productivity (Patil & Gokhale, 2022). This interdependence is critical for deploying the GBOS framework, where sustainable innovations are driven by leveraging data analytics for cost-efficient solutions. By combining AI's data processing capabilities with IoT's extensive data collection infrastructure, firms can enhance their adaptability to market changes, thereby supporting frugal innovation. This approach addresses resource limitations, encourages sustainable development, and expands the accessibility of creative solutions to marginalized communities.

Artificial Intelligence (AI) enables cost-effective innovators to achieve superior performance by efficiently utilizing limited resources to offer solutions that involve understanding customer preferences (Cheng & Jiang, 2021; Xu et al., 2020), and enhancing outcomes from online customer engagement behaviors, whether solicited or unsolicited, through the use of information processing systems (Perez-Vega et al., 2021). AI improves the automation and effectiveness of marketing procedures (Esch & Black, 2021; Overgoor et al., 2019), optimizes the utilization of marketing data (Stone et al., 2020), and aids in the analysis of market trends and client requirements. This analysis helps businesses develop new goods and services even when they have limited financial resources, a practice known as "frugal innovation" (Huang & Rust, 2020; Jabeur et al., 2022). Thus, artificial intelligence plays a critical role in improving a business's operational efficiency and fostering long-term success.

Green Blue Ocean Strategy (GBOS)

Achieving a blue economy is challenging due to issues in various sectors, including business and government. The Green Blue Ocean Strategy (GBOS) extends the Blue Ocean Strategy (BOS) by embedding sustainability as a core principle, addressing the dual goals of economic growth and environmental preservation. Unlike traditional BOS, which focuses on creating uncontested market spaces, GBOS prioritizes innovations that align with ecological goals and global sustainability standards (Brozović et al., 2020; Freudenreich et al., 2020). This study differentiates GBOS from existing frameworks like sustainability-driven innovation by demonstrating its application in integrating AI and IoT for cost-efficient, eco-friendly solutions. Unlike traditional BOS, which focuses solely on untapped markets, GBOS emphasizes sustainable value creation by aligning economic and environmental objectives. This approach leverages unique resources to create value while addressing ecological concerns, differentiating it from sustainability-driven innovation frameworks (Brozović et al., 2020; Freudenreich et al., 2020). Policymakers have utilized recent advancements in the blue economy to effectively screen and regulate blue products and industrial chains, promoting sustainable development in this sector (Ni et al., 2024). Adopting a comprehensive strategy that fosters a blue economy by combining sustainable environmental management with economic growth is imperative. The Green Blue Ocean Strategy (GBOS) and the Blue Ocean Strategy (BOS) differ primarily in that BOS emphasizes expanding into untapped markets and avoiding competition.

However, the literature lacks comprehensive discussions on how GBOS integrates with digital innovations like AI and IoT. This study addresses this gap by exploring how GBOS can enhance the deployment of IoT and AI to drive sustainable innovation. GBOS can enhance organizational resilience by promoting eco-friendly innovations while reducing competitive pressures (El-Kassar & Singh, 2019; Song & Yu, 2018). In contrast, GBOS integrates environmental sustainability as a fundamental aspect of innovation and value development. Unlike the traditional Blue Ocean Strategy (BOS), which focuses solely on expanding into untapped markets, the Green Blue Ocean Strategy (GBOS) integrates environmental sustainability into strategic innovation efforts (Daly et al., 2021; Soma et al., 2018).

GBOS differentiates itself by emphasizing the simultaneous pursuit of economic growth and ecological preservation, thus aligning with sustainability-driven innovation frameworks. This study fills a gap in the literature by demonstrating how GBOS can be operationalized through the integration of AI and IoT to drive sustainable frugal innovation in resource-constrained settings. Recent research shows that an organizational culture valuing ecological sustainability and sharing a vision for protecting the environment can help spread green practices, which in turn improves the success of developing

eco-friendly products (Chen et al., 2020). Aligning economic goals with sustainable development objectives becomes even more crucial by incorporating environmental principles into strategic innovation frameworks. GBOS extends the RBV framework by integrating IoT and AI as strategic resources that fulfill VRIO criteria—valuable, rare, inimitable, and organized—driving sustainable innovation and competitive advantage in resource-constrained environments

Frugal innovation (FI)

According to Dabić et al. (2022), frugal innovation in transdisciplinary science aims to do more with fewer resources. Frugal Innovation (FI) focuses on maximizing resource efficiency, particularly in contexts with limited resources (Albert, 2019). The integration of IoT and AI enhances the capacity for FI by enabling firms to utilize real-time data analytics to optimize processes and reduce costs. This study explores how leveraging AI within the GBOS framework can drive frugal innovation by creating low-cost, sustainable solutions tailored to developing markets. In health sciences, empirical evidence addresses the challenge of innovation with constrained resources (Chakravarty, 2022). Prior scientific research has highlighted risk-taking behavior, proactiveness (Dost et al., 2019), leadership (Iqbal & Piwowar-Sulej, 2023), and resource constraints at the company level (Ploeg et al., 2021) as critical factors in frugal innovation. Weyrauch and Herstatt (2017) argue that the features of AI enable the development of inexpensive products and services that meet users' needs in emerging economies. Consequently, FI is essential to technological development in poor nations because scarce resources require creative solutions (Sarkar & Mateus, 2022). Furthermore, FI ensures the accessibility of cost-effective goods, tackling issues such as limited finances, infrastructure, and human resources. This promotes economic innovation in emerging economies (Zeschky et al., 2014) and facilitates the adoption of ecologically sustainable practices for the future (Levänen et al., 2016). Frugal innovation and cost-effective solutions to developing countries' unique challenges can promote sustainable growth.

Figure 1 presents the empirical research model:

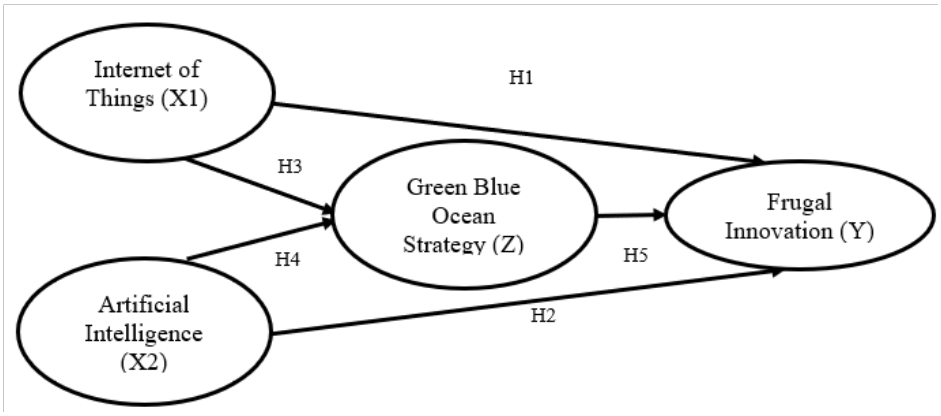

Figure 1: Empirical research model

The impact of Internet of Things and Artificial Intelligence on frugal innovation

To overcome fundamental resource limits, the Internet of Things (IoT) has become crucial in frugal innovation (Park et al., 2022; Quan et al., 2019). Although IoT holds great potential, various hurdles prevent its mainstream implementation. These include a lack of specialists with the expertise to manage IoT devices, additional expenses for staff training and device purchases, and significant privacy and security concerns. Moreover, the complexity is compounded by internet connectivity issues, industry participants' awareness, regulatory requirements, and government enforcement (Dosumu & Uwayo, 2023). The implementation of IoT can present risks and obstacles that may disrupt organizational processes, potentially resulting in financial losses (Mercan et al., 2020). Problems with IoT technology, questions about its benefits and costs, and external pressures for its adoption pose challenges to acceptance in many areas, such as transportation and supply chain management (Tu, 2018). Furthermore, several research findings highlight negative interaction factors from IoT, particularly in developing countries with limited resources, where the ability to adopt IoT technology effectively is constrained. Implementing IoT technology in developing nations with limited resources presents significant challenges. As interconnectivity grows, the likelihood of privacy breaches and security risks also increases, making IoT deployments more vulnerable.

The Resource-Based View (RBV) theory influences how AI and frugal innovation (FI) affect company performance. AI enhances operational efficiency and adaptability to market changes (Åström et al., 2022). The RBV emphasizes unique resources and capabilities as key to sustainable competitive advantage. AI, through intelligent marketing automation, improves sales forecasting and operational procedures, thereby boosting firm performance (Ameen et al., 2022; Paschen et al., 2019). Frugal innovation enables companies to use limited resources creatively to innovate. Levänen et al. (2016) found that AI and frugal innovation can maximize resource potential, operational efficiency, and quality product production at low cost. FI helps organizations produce cheaper and more effective goods and services, enhancing their competitiveness (Jayabalan et al., 2021). Thus, a strong hypothesis is that AI and frugal innovation, guided by RBV principles, optimize resources for sustainable innovation and growth. These hypotheses are formulated based on the theoretical understanding that while IoT provides data infrastructure, its adoption might face barriers due to high costs and resource constraints in MSMEs. In contrast, AI's capability to analyze data and optimize operations directly supports frugal innovation. GBOS, as a mediator, integrates these technologies into a cohesive framework that overcomes these barriers, enabling sustainable and cost-effective innovation. The literature review above leads to the following hypothesis:

H1: Internet of Things (IoT) influences frugal innovation negatively.
H2: Artificial Intelligence influences frugal innovation positively.

The impact of Internet of Things and Green Blue Ocean Strategy

With improved connectivity and automation, Internet of Things (IoT) technology has enormous potential to transform businesses completely The Green Blue Ocean Strategy enables organizations to achieve sustainability and drive innovative growth in unexplored markets simultaneously. The Resource-Based View (RBV) emphasizes the importance of a company's distinctive resources in establishing long-lasting competitive advantages (Barney & Hesterly, 2019). Integrating IoT with the Green Blue Ocean Strategy has the potential to become a beneficial strategic resource. By using IoT effectively, businesses can improve their data analysis, automation, and operational efficiency. This can lead to new market opportunities for innovation and value creation (Olorunyomi Stephen Joel et al., 2024; Shahi & Sinha, 2020). This integration could result in the identification of novel "blue oceans," characterized by limited competition because of the generation of distinctive value. IoT can also create new resources and skills, giving businesses a more potent edge in a business world that is becoming more complex and rapidly changing (Markfort et al., 2021). So, the hypothesis that can be developed is:

H3: Internet of Things (IoT) influences Green Blue Ocean Strategy positively.

The impact of Artificial Intelligence and Green Blue Ocean Strategy

The Green Blue Ocean Strategy (GBOS) focuses on creating new markets by minimizing competition, while Frugal Innovation (FI) is concerned with efficiently using resources to develop quality products and services at low costs. This aligns with one of the FI criteria (Barney, 1991; Barney, 1995). AI can help companies optimize their operations, while the Green Blue Ocean Strategy aims to create new market space by minimizing competition. When these two concepts are combined, companies can leverage AI to increase efficiency and innovation in creating new products and services. At the same time, a Green Blue Ocean Strategy ensures that these products and services are unique and difficult for competitors to replicate. The research findings of Kamble et al. (2020), emphasize that integrating AI with other information technologies has significantly increased product and service innovation. This solution efficiently uses resources while maintaining quality, aligning with frugal innovation's goals. In line with Boons and Lüdeke-Freund (2013), frugal innovation is essential to create value through cost efficiency in developing cost-effective methods, especially when facing global economic challenges. Furthermore, AI supports this logistics relationship, namely: 1) AI helps companies improve tactics by utilizing real-time data to respond quickly to market changes in line with GBOS principles (Qin, 2024); 2) AI assists companies run GBOS by gaining strategic insights through data analysis, enabling identifying new market opportunities and tailoring products or services to the unique needs of those markets (Jarrahi, 2018); 3) AI allows companies to produce innovative products or services at low costs, and continuously adapt to market competition, which is the essence of the GBOS concept (Erik & Andrew, 2017). Therefore, based on the explanation above, the hypothesis that can be proposed in this relationship is:

H4: Artificial Intelligence influences Green Blue Ocean Strategy positively.

The impact of Green Blue Ocean Strategy and frugal innovation

The Green Blue Ocean Strategy (GBOS) aims to create new markets by reducing rivalry. Frugal Innovation (FI) optimizes resource utilization to create high-quality products and services at minimal expense. This is consistent with one of the criteria for frugal innovation provided by Weyrauch and Herstatt (2017), which involves reducing excessive costs, focusing on essential functions, and enhancing optimal performance. The Resource-Based View (RBV) methodology applies to financial institutions' criteria regarding the caliber of a company's distinctive resources in creating a sustainable competitive advantage (Barney & Clark, 2007). Although little literature explicitly examines the connection between GBOS and FI, earlier studies have explored the potential of frugal innovations for market attractiveness (Albert, 2019; Dima et al., 2022). Due to its potential synergistic convergence with GBOS principles in structuring critical strategies for pursuing innovation, environmental sustainability, and market formation, the FI concept emerges as an appealing paradigm. GBOS offers the potential to circumvent saturated markets (red oceans) and establish pioneering industrial success in ecological, social, and governance accomplishments (Markopoulos & Ramonda, 2022). Ultimately, GBOS can push businesses to develop new products and ideas by combining ambition, social impact, and profit, helping them follow global innovation trends and build long-lasting wealth for society. Thus, a beneficial effect on FI is anticipated from deploying GBOS.

H7: The Green Blue Ocean Strategy (GBOS) directly and positively influences frugal innovation by integrating ecological considerations into resource optimization.

Internet of Things on frugal innovation through Green Blue Ocean Strategy

The acquisition and development of value-based, rare, inimitable, and organized (VRIO) internal resources, coupled with sustainable development approaches, alliance and partnership strategies, and a robust organizational culture, are critical to improving corporate performance (Barney, 1991; Barney & Hesterly, 2019). As firms aim to improve their business operations, IoT technology becomes essential for making informed decisions (Brous et al., 2019; Chatterjee et al., 2024). The Internet of Things (IoT) can stimulate economic innovation through its ability to enhance data collection efficiency (Andrade et al., 2023), enable automation and remote control (Froiz-Míguez et al., 2018), detect device or machine failures in advance (Banaamah & Ahmad, 2022) and facilitate the development of novel business models (Ceipek et al., 2020). A Green Blue Ocean Strategy encourages economic innovation. IoT is crucial because it provides data analysis and insights from technological solutions that help markets stay open and stand out in the long term. The Green Blue Ocean Strategy (GBOS) mediates the relationship between Internet of Things (IoT) and frugal innovation, enabling firms to leverage real-time data for sustainable and cost-efficient product development (Ni et al., 2024). This hypothesis explores how IoT, through the GBOS framework, enhances operational efficiencies and market responsiveness in resource-limited environments. As a result, the Green Blue Ocean Strategy aims to improve and propel the blue ocean strategy towards attaining corporate objectives in a sustainable and eco-friendly manner. The results of this hypothesis can be developed:

H5: The significant effect of Internet of Things on frugal innovation mediated by Green Blue Ocean Strategy.

Artificial Intelligence on frugal innovation through Green Blue Ocean Strategy

Innovation is emphasized in a blue ocean strategy by providing new, distinctive goods or services that build demand beyond the reach of irrelevant competitors (Kim & Mauborgne, 2017). This lack of relevance motivates ongoing enhancement in the intangible assets of human knowledge and abilities. Nevertheless, the limits inherent in human understanding often necessitate assistance to keep up with innovation demands. The Knowledge-Based View (KBV) was created by recognizing these limitations and adding knowledge assets to the Resource-Based View (RBV). The Knowledge-Based View (KBV) highlights the importance of diverse knowledge bases and competencies for company success, especially in knowledge-intensive economies (Cuthbertson & Furseth, 2022; Grant, 1996). Artificial Intelligence (AI) is of utmost importance as it utilizes computer algorithms to imitate intelligent human behavior when carrying out intricate activities (Akçay & Etiz, 2020; Morandín-Ahuerma, 2022). Prior studies emphasize the impact of AI in facilitating cost-effective innovation by advancing sustainability (Qin, 2024). To prevent complacency, GBOS must adopt a strategy that aligns with transitioning

from a Resource-Based View (RBV) to a Knowledge-Based View (KBV). This approach should involve utilizing physical and knowledge-based resources to promote sustainable innovation.

When AI is integrated with GBOS, businesses can find new opportunities, avoid direct competition by opening up new markets with creative AI solutions, optimize resources in business processes, and identify environmental issues sooner. Artificial Intelligence (AI) enhances the impact of the Green Blue Ocean Strategy (GBOS) on frugal innovation by providing tools for data-driven decision-making, optimizing resource allocation, and enabling the development of sustainable, low-cost products (Govindan, 2022; Jankovic & Curovic, 2023). This integration helps firms identify new market opportunities while minimizing competition. These factors provide significant leverage for economic innovation (Ma et al., 2020). AI can enhance the connection between GBOS and frugal innovation by providing tools for in-depth data analysis, forecasting market trends, and creating sustainable and cost-effective products or services. These hypotheses reflect the interdependence of AI and IoT technologies in driving sustainable innovation within the GBOS framework, ensuring that firms can achieve long-term competitive advantages through resource optimization and sustainability.

H6: The Green Blue Ocean Strategy (GBOS) mediates the positive impact of Artificial Intelligence (AI) on frugal innovation by facilitating sustainable and cost-efficient strategies.

METHODOLOGY

Research design and sample

This study employed a quantitative approach to test six hypotheses. The respondents in this study were collected through questionnaires distributed to 285 MSMEs in the creative business sector in Central Java, Indonesia. However, only 262 samples were considered complete for data processing. To establish a rigorous foundation for the Green Blue Ocean Strategy (GBOS), this study systematically developed the concept through three stages:

1) Theoretical synthesis: The GBOS framework integrates core principles from Blue Ocean Strategy (Kim & Mauborgne, 2004; Kim & Mauborgne, 2017), sustainability-driven innovation (Xie et al., 2019) and Resource-Based View (RBV) (Barney, 1991). This synthesis identifies the gap in existing strategic frameworks by incorporating sustainability as a central element in market expansion.
2) Empirical validation: The study empirically tests GBOS using Structural Equation Modeling (SEM) with AMOS based on survey data from 262 creative entrepreneurs in Central Java, Indonesia. The construct validity and reliability of GBOS were assessed using Confirmatory Factor Analysis (CFA) to ensure its robustness as a measurable construct.
3) Comparative analysis: GBOS is compared with existing sustainability frameworks such as Green Process Innovation (Xie et al., 2019) and Blue Economy models (Soma et al., 2018) to highlight its novel contribution. Unlike prior models that focus solely on environmental or market expansion strategies, GBOS uniquely integrates cost-efficiency, ecological sustainability, and digital transformation (IoT & AI) into a unified strategic framework

The purposive sampling method was utilized to ensure that respondents possessed sufficient exposure to digital technologies, which is essential for assessing the impact of AI and IoT on business innovation. Given that the study focuses on GBOS and frugal innovation, targeting respondents with a demonstrated use of digital tools helps provide more accurate insights into the research questions. This approach is aligned with previous studies that emphasize the importance of targeted sampling in technology adoption research. This study employed a quantitative approach to test seven hypotheses. The purposive sampling method was chosen to target MSMEs in the creative business sector who are actively utilizing digital technologies such as AI and IoT for business development (Hosseini & Rajabipoor Meybodi, 2023; Liu et al., 2020). Respondents were selected not only based on their industry but also on their demonstrated engagement with digital technologies, ensuring that the sample is relevant to the research objectives, particularly in examining the impact of digital competencies on frugal innovation. The respondents were specifically selected from sectors with varying levels of digital adoption, such as Film, Animation, Culinary, and App Development, to assess their technological competence.

Additionally, a digital competency assessment was included in the questionnaire to ensure that respondents possessed the necessary technological understanding to provide informed responses. To address the concerns regarding the digital competency of respondents, this study included a section in the questionnaire to assess their familiarity with IoT and AI technologies. Respondents were asked to rate their proficiency in using digital tools on a 5-point Likert scale, where 1 =

No experience and 5 = Expert level. The results indicated that 74% of the respondents rated themselves at level 3 or above, suggesting adequate competencies to participate in this study. The inclusion of specific questions in the questionnaire (IoT_3 and AI_1) ensures that respondents can provide informed answers based on their practical exposure to these technologies. This approach strengthens the validity of the data collected. The questionnaires that had been returned with complete answers were further tested to confirm the RBV approach related to the empirical data within the research constructs. Despite the strengths of the sampling approach, it is acknowledged that purposive sampling may introduce bias due to the non-random selection of respondents. Additionally, the cross-sectional nature of the study limits the ability to infer causality over time. Future studies are encouraged to adopt longitudinal designs to better understand the evolving impact of digital technologies on frugal innovation.

In this study, respondents were not solely chosen based on their industry affiliation (Film and Culinary sectors) but were also selected based on an objective assessment of their digital competence. This decision was driven by the varying levels of technology adoption within these industries. In the Film industry, digital technologies such as IoT and AI are increasingly utilized in production and distribution for automated video editing, audience data analysis, and content distribution optimization. However, the degree of technology adoption varies significantly depending on the scale and technological capabilities of the company. Therefore, merely being part of the film industry does not guarantee that respondents possess the necessary digital competence to evaluate technologies like IoT and AI (Daniels et al., 2019). Similarly, in the culinary sector, IoT and AI are used in areas such as supply chain optimization, inventory management, and customer preference analysis. Although these technologies play an essential role, their adoption and understanding can vary widely among businesses (Wu et al., 2022). Therefore, assessing digital competence was crucial to ensure that respondents could provide informed insights into the application of these technologies. To enhance the validity of the data collected, a digital competence assessment was integrated into the questionnaire. This ensured that only respondents with a genuine understanding of IoT and AI technologies were included, thereby strengthening the robustness of the analysis (Trenerry et al., 2021).

This study utilized Structural Equation Modeling (SEM) with the AMOS program to test the research hypotheses. A quantitative approach for data analysis with Structural Equation Modeling in the AMOS 21 program was employed for this research. To validate the measurement instruments, convergent validity was assessed using Average Variance Extracted (AVE) values, with all constructs exceeding the 0.5 threshold. Reliability was evaluated through Composite Reliability (CR), with values above 0.7 confirming the consistency of the constructs (Anderson & Gerbing, 1988). These steps ensure that the measurement model meets the criteria for validity and reliability, aligning with SEM best practices. The Maximum Likelihood Estimation (MLE) method was applied, given its robustness in handling multivariate normality and ensuring the reliability of the path coefficients. The multivariate normality requirement in SEM testing was necessary to estimate the structural (path) coefficients. MLE required endogenous variables to be normally distributed (Anastasiou & Gaunt, 2020). This method aligns with the study's objective of empirically validating the impact of IoT and AI on GBOS and frugal innovation. The measurement model applied convergent validity to ensure the validity of the indicators in measuring the tested variables. The significance of the indicators assessed the appropriateness of the indicators in forming the latent variables. Therefore, the SEM analysis was performed by testing the goodness of fit parameters and the research hypotheses on the causal relationships in the model. The SEM assumptions that were required to be met included a small Chi-Square value, Probability ≥ 0.05, CMIN/DF ≤ 2.00, GFI ≥ 0.90, AGFI ≥ 0.90, TLI ≥ 0.95, CFI ≥ 0.95, and RMSEA ≤ 0.08 (Arbuckle, 2011).

The reason for selecting this region was the presence of creative MSME clusters currently utilizing technology for business development. Secondly, the collection of empirical data confirmed how resource limitations, particularly cost efficiency, could be reduced using AI and IoT in areas that had relatively low regional income. Thirdly, by leveraging the government's Go-Digital MSME program, it was anticipated that businesses could continue to innovate cost-effectively while maintaining environmental sustainability. This study aimed to empirically demonstrate the impact of independent variables on dependent variables. The author collected data by distributing questionnaires to the research sample. The sample characteristics were presented in Table 1 below.

Table 1. Respondents of the research sample

Sample characteristics	Description	Number of samples	Percent
Educational Level	Elementary	23	8.78
	Junior high school	34	12.98
	Senior high school	76	29.01
	Diploma	34	12.98
	Bachelor's degree	95	36.26
Age	< 25	40	15.27
	26 - 30	32	12.21
	31 – 35	62	23.66
	36 – 40	78	29.77
	41 – 45	29	11.07
	> 45	21	8.02
Sector Creative:	Photography	18	6.87
	Film, Animation, and Video	32	12.21
	Publishing	21	8.02
	Advertising	19	7.25
	Visual Communication Design	17	6.49
	Music	18	6.87
	Television and Radio	5	1.91
	Product Design	24	9.16
	Apps and Game Developers	19	7.25
	Art	18	6.87
	Fashion	22	8.40
	Interior Design	17	6.49
	Culinary	20	7.63
	Architecture	12	4.58
Operating Duration	< 3 years	48	18.32
	> 3 to 5 years	104	39.69
	> 5 to 10 years	85	32.44
	> 10 years	25	9.54
Average income per month	< IDR 5 million	69	26.34
	> IDR 5 million to 10 million	79	30.15
	> IDR 10 million	114	43.51
Number of employees	< 5 persons	117	44.66
	> 5 to10 persons	89	33.97
	> 10 persons	56	21.37
Business capital	< IDR 25 million	145	55.34
	> IDR 25 million to 50 million	72	27.48
	> IDR 50 million	45	17.18

Note: n = 262.

Variable and measurement of construct

This study used a quantitative research design to test hypotheses and the empirical research model. The research sample was drawn from a cluster of creative MSME industries by identifying four relevant constructs: IoT, AI, GBOS, and FI. A thorough literature review was conducted to identify the research variables, followed by reliability and validity testing. Each construct was measured using a 7-point Likert scale (1 = strongly disagree to 7 = strongly agree). The endogenous constructs in this study were GBOS and FI, while the exogenous constructs were IoT and AI.

This study included dimensions for each construct. The exogenous construct of IoT had two dimensions: first, resource usage management, which was measured with three statements, and second, integration with cost-effective innovation, which was measured with four statements. The artificial intelligence construct had three dimensions: resource efficiency improvement (REI), sustainable supply chain management (SSCM), and lifecycle impact reduction (LIR). REI was reflected by two statements, SSCM was measured with two statements, and LIR was reflected by two statements. The GBOS construct had two dimensions: sustainable value creation, which consisted of three items, and sustainable value proposition, which consisted of three items. For FI, there were six statement items in total, with the first three items from the dimension of Sustainable Creative Product Development and the next two statements from the dimension of Affordability and Accessibility. Each statement item within the dimensions was described in Table 3. Thus, a total of 24 statement items were tested to measure each construct.

RESULTS

Descriptive statistics and correlations

IoT, AI, GBOS, and FI are presented in Table 2 as descriptive data and correlation matrices. The table also provides the average values, standard deviations, and correlation matrix of the study variables. The means range between 3.45 and 3.71, indicating that the level of adoption is moderate to high. The responses are consistent, as evidenced by the standard deviations ranging from 0.72 to 0.81. The correlations are strong and positive, with GBOS and FI showing the strongest connection (0.75). These figures support the testing models for the hypotheses. More specifically, the 0.63 correlation between AI and FI indicates a strong positive relationship, suggesting that greater AI usage is associated with higher FI.

Table 2. Mean, standard deviation, and correlation of the construct

Construct	Mean	Std. Dev.	IoT	AI	GBOS	FI
IoT	3.45	0.76	1	0.65	0.70	0.60
AI	3.52	0.81	0.65	1	0.68	0.63
GBOS	3.68	0.72	0.7	0.68	1	0.75
FI	3.71	0.78	0.6	0.63	0.75	1

Note: IoT: Internet of Things; AI; Artificial Intelligence GBOS: Green Blue Ocean Strategy; FI: Frugal Innovation. The p-values for the correlations between constructs are not displayed in this table but are statistically significant at the 0.05 level. Correlations represent the strength and direction of relationships between constructs, with values closer to 1 indicating a stronger positive relationship.

Validity and reliability testing

This study assessed validity by conducting confirmatory factor analysis (CFA) and evaluated reliability by examining construct reliability using the Critical Ratio (CR) value. Additional testing was performed to determine the values of Construct Reliability (CR), Average Variance Extracted (AVE), and Discriminant Validity (DV) for each exogenous and endogenous construct. The validity and reliability of each construct were evaluated by analyzing the coefficient alpha value. As shown in Table 3, the constructs of IoT, AI, GBOS, and FI not only met but significantly exceeded the necessary conditions for validity and reliability, with values greater than 0.7. The test findings for the average variance extracted value indicated a value above 0.5, further reinforcing the robustness of the constructs. The Discriminant Validity value for each construct exceeded 0.7, providing strong evidence of their distinctiveness. Table 3 presents the computations for assessing validity and reliability using the AMOS program, underscoring the thoroughness of the analysis.

Table 3. Scale item for measures

Variable	Indicator	Scale item	Reference	Std. loading (Lambda value)	Critical ratio ≥1.96
Internet of Things	RUM_1	Our business has used IoT to cut down on energy use	Adapted from: Azzawi et al. (2016); Bhatti (2012); Govindan (2024); Qin (2024); Sullivan et al. (2023); Tiwari (2021)	0.803	-
	RUM_2	With the help of IoT, our company has been able to cut down on material loss.		0.733	11.291
Construct Reliability = 0.703	RUM_3	IoT systems let businesses keep an eye on how resources are being used and report on it in real time.		0.793	11.952
AVE = 0.574	ICEI_1	Our company uses IoT to make successful products and services that meet the wants of the market at a low cost.		0.750	-
	ICEI_2	Our company's IoT products can give more people access and reach a wider audience, even those with low incomes.		0.773	11.433
	ICEI_3	Using IoT to improve innovation has led to big results for both our business and outside groups.		0.692	10.346
	ICEI_4	Our company has been able to successfully bring IoT applications to new places.		0.751	11.162
Artificial Intelligence	REI_1	Our business uses AI to make the best use of energy in its processes.	Adapted from: Alliance (2020); Govindan (2024); Masanja and Mkumbo (2020); Qin (2024); Stroumpoulis et al. (2022); Thakare et al. (2022)	0.833	-
	REI_2	AI is used by our company to help find energy waste and leaks.		0.681	10.637
Construct Reliability = 0.847	SSCM_1	AI is used by our company to find sources that meet environmental standards.		0.867	-
AVE =0.719	SSCM_2	Using AI helps people decide what to buy.		0.786	11.712
	LIR_1	Our business makes products that are better for the world.		0.817	6,406
	LIR_2	With the help of artificial intelligence, goods can last longer.		0.814	6.406
Green Blue Ocean Strategy	SVC_1	Implement strategies to reduce the environmental impact throughout the lifecycle of products.	Adapted from: Ottman and Books (1998); Pickett-Baker and Ozaki (2008); Russo and Fouts (1997); Sen and Bhattacharya (2001)	0.689	-
	SVC_2	Enhance the efficiency of resources.		0.786	10.502
Construct Reliability = 0.775 AVE = 0.708	SVC_3	Integrate sustainability into supply chain, from sourcing to distribution.		0.760	10.274
	SVP_1	Offer products with specific green features that reduce environmental impact		0.593	-
	SVP_2	Build a reputation for sustainability that enhances brand value and customer loyalty		0.800	8.738
	SVP_3	Acquire environmental certifications and labels to communicate our commitment to sustainability to customers		0.737	8.481
Frugal Innovation	SCPD_1	When our company makes products, we consider how they will affect the world.	Adapted from: Bhatti (2012); Govindan (2024); Hossain et al. (2023); Park et al. (2018); Qin (2024)	0.777	-
CR = 0.711 AVE = 0.602	SCPD_2	Our business uses data analysis and AI predictions to find trends.		0.701	8.709
	SCPD_2	When it comes to using eco-friendly materials in new ways, our company is proud.		0.723	-
	AA_1	Our business is done so that people from all walks of life can use it.		0.709	9.654
	AA_2	Our company uses IoT technology to lower output costs and make them affordable.		0.712	9.684

Note: RUM: Resource Usage Management; ICEI: Integration with Cost effective Innovation SSCM: Sustainable Supply Chain management; LIR: Lifecycle Impact Reduction; SVC: Sustainable Value Creation; SVP: Sustainable Value Proposition; SCPD: Sustainable Creative Product Development; AA: Affordability and Accessibility; AVE: Average Variance Extracted; CR: Construct Reliability.

The loading factor values demonstrated the reliability and validity of the four constructs: IoT, AI, GBOS, and FI. The IoT loading factor value was divided into two parts: Resource Usage Management (RUM) and Integration with Cost-effective Innovation (ICEI). The four indicators for RUM were 0.803, 0.733, and 0.793 for RUM_1, RUM_2, and RUM_3, respectively. The four indicators for ICEI were 0.750, 0.773, 0.692, and 0.751 for ICEI_1, ICEI_2, and ICEI_3, respectively.

Artificial intelligence was divided into three components: Resource Efficiency Improvement (REI), Sustainable Supply Chain Management (SSCM), and Lifecycle Impact Reduction (LIR). The AI values were 0.833 for REI_1, 0.681 for REI_2, 0.867 for SSCM_1, 0.786 for SSCM_2, and 0.817 and 0.814 for LIR_1 and LIR_2, respectively. Sustainable Value Creation (SVC) and Sustainable Value Proposition (SVP) comprised the two components of GBOS. For items SVC_1, SVC_2, and SVC_3, the loading factor values were 0.689, 0.786, and 0.760, respectively. The loading factors for SVP_1, SVP_2, and SVP_3 were 0.593, 0.800, and 0.737, respectively. Finally, FI consisted of two components: Affordability and Accessibility (AA) and Sustainable Creative Product Development (SCPD). The SCPD values were 0.777 for SCPD_1, 0.701 for SCPD_2, and 0.723 for SCPD_3. The values for AA_1 and AA_2 were 0.709 and 0.712, respectively.

The construct reliability of the IoT, AI, GBOS, and FI constructs was demonstrated by values exceeding 0.7. The average variance extracted value also exceeded 0.5. The validation testing for IoT, AI, GBOS, and FI is summarized in Table 3. A loading factor value greater than 0.6, as defined by Hair et al. (2013)U, is the necessary criterion. Therefore, the four constructs were deemed valid.

Discriminant validity

The discriminant validity values for the GBOS, FI, AI, and IoT variables are presented in Table 4. To assess discriminant validity, the square root of the Average Variance Extracted (AVE) for each construct must be examined and compared to the correlations between the constructs. A construct is considered discriminant valid if its square root of AVE is higher than its correlations with other constructs. The constructs used in this study were valid because IoT, AI, GBOS, and FI all demonstrated good discriminant validity, indicating that they each measured a distinct aspect of the data.

Table 4. Discriminant validity

Variable		**GBOS**		**FI**		**AI**			**IoT**	
SVP		**SVC**	**AA**	**SCPD**	**SSCM**	**REI**	**LIR**	**ICI**	**RUM**	
GBOS	SVP	**0.715**								
	SVC	0.704	**0.746**							
FI	AA	0.573	0.634	**0.715**						
	SCPD	0.556	0.615	0.602	**0.740**					
AI	SSCM	0.410	0.454	0.538	0.522	**0.827**				
	REI	0.502	0.556	0.659	0.640	0.751	**0.761**			
	LIR	0.413	0.457	0.542	0.527	0.618	0.757	**0.816**		
IoT	ICI	0.338	0.375	0.298	0.290	0.242	0.297	0.244	**0.742**	
	RUM	0.362	0.401	0.319	0.310	0.259	0.317	0.261	0.573	**0.777**

Source: Data Processed from software AMOS.

Structural model

Hypothesis testing

The table presents the discriminant validity values for the GBOS, FI, AI, and IoT factors. To assess discriminant validity, the square root of the Average Variance Extracted (AVE) for each construct should be compared to the correlations between the constructs. A construct exhibits discriminant validity if its square root of AVE is higher than the correlations with other constructs. The research models were considered valid because IoT, AI, GBOS, and FI all demonstrated the ability to distinguish between different data types and showed strong discriminant validity.

Table 5. Results of the hypothesis testing and goodness-of-fit analysis

Hypothesis variable		**Std estimate**	**Coefficient**	**T value**	**P**	**Conclusion**
H1	IoT → FI	0.079	-0.036	-0.460	0.646	Not supported
H2	IoT → GBOS	0.074	0.255	3.456	***	Supported
H3	AI → FI	0.064	0.271	4.250	***	Supported
H4	AI → GBOS	0.052	0.251	4.837	***	Supported
H5	GBOS mediates the influence of IoT to FI	Full-mediation effect is confirmed.				
	Mediation Process	Std estimate	Coefficient	T-value	P	Conclusion
	P1: IoT → GBOS	0.048	0.358	7.432	***	Supported
	P2: GBOS → FI	0.456	0.502	11.000	***	Supported
	P3: IoT → FI	0.429	0.258	6.018	***	Supported
	P4: IoT → FI	0.390	0.078	2.006	0,458	Not supported
H6	GBOS mediates the influence of AI to FI	Full-mediation effect is confirmed.				
	P1: AI → GBOS	0.418	0.377	9.032	***	Supported
	P2: GBOS → FI	0.411	0.349	8.494	***	Supported
	P3: AI → FI	0.313	0.435	13.923	***	Supported
	P4: AI → FI	0.318	0.303	9.557	***	Supported
H7	GBOS → FI	0.175	0.689	3.949	***	Supported
Goodness of fit Test				Cut-off value	Result	Conclusion
Significance of Chi-square				≥0.05	0.000	Poor fit
The goodness of Fit Index				≥0.90	0.919	Fit
The Adjusted Goodness of Fit Index				≥0.90	0.879	Marginal fit
Comparative Fit Index				≥0.90	0.958	Fit
Tucker Lewis Index				≥0.90	0.952	Fit
RMSEA-Root mean square error of approximation				0.03 – 0.08	0.042	Fit

Note: ***p <0.05.
Source: Data Processed from software AMOS.

Table 5 presents the full structural equation model employed to examine the empirical research model:

- IoT did not have a significant effect on FI, as indicated by the p-value for H1 (0.646), which exceeds the significance level of 0.05, and the negative path coefficient (-0.036). These results provide insufficient evidence to establish a significant relationship between IoT and FI. Consequently, hypothesis 1 is not supported.
- H2, regarding how IoT affected GBOS, had a path coefficient value of 0.255 and a significance value of 0.000, suggesting that IoT positively impacted GBOS. Therefore, hypothesis 2 was confirmed.
- AI had a substantial positive impact on FI, as evidenced by the path coefficient value of 0.271 and the significance value of 0.000 for H3. Therefore, hypothesis 3 was confirmed.
- H4 showed a significant positive influence of AI on GBOS, with a significance value of 0.000 and a path coefficient value of 0.251. Therefore, hypothesis 4 was confirmed.
- H5, which examined GBOS's mediating role in the relationship between IoT and FI, revealed that the direct impact of IoT on FI was no longer significant when GBOS was included in the regression model. The study found that including GBOS in the regression model did not eliminate AI's significant direct influence on FI. This suggests that GBOS partially mediates the association between AI and FI.
- H6, which tested the mediating role of GBOS in the relationship between AI and FI, indicates that GBOS acts as a significant mediator. This is evidenced by the substantial positive impact of AI on GBOS (0.377, $p < 0.05$), and the effect of GBOS on FI (0.349, $p < 0.001$). Therefore, hypothesis 6 is supported, suggesting that GBOS fully mediates the relationship between AI and FI.
- GBOS significantly enhanced FI, as shown by H7's significance value of 0.000 and a path coefficient value of 0.689. Therefore, hypothesis 7 was confirmed.

Overall, the findings confirmed hypotheses 2, 3, and 4, as well as the mediation processes outlined in hypotheses 5 and 6. However, hypothesis 1 was not supported by the results. Based on the findings, GBOS plays a significant role in how IoT and AI affect FI. This underscores the importance of employing Green Blue Ocean Strategy to enhance cost-effective innovation. The connection model between IoT, AI, GBOS, and FI is illustrated in Figure 2.

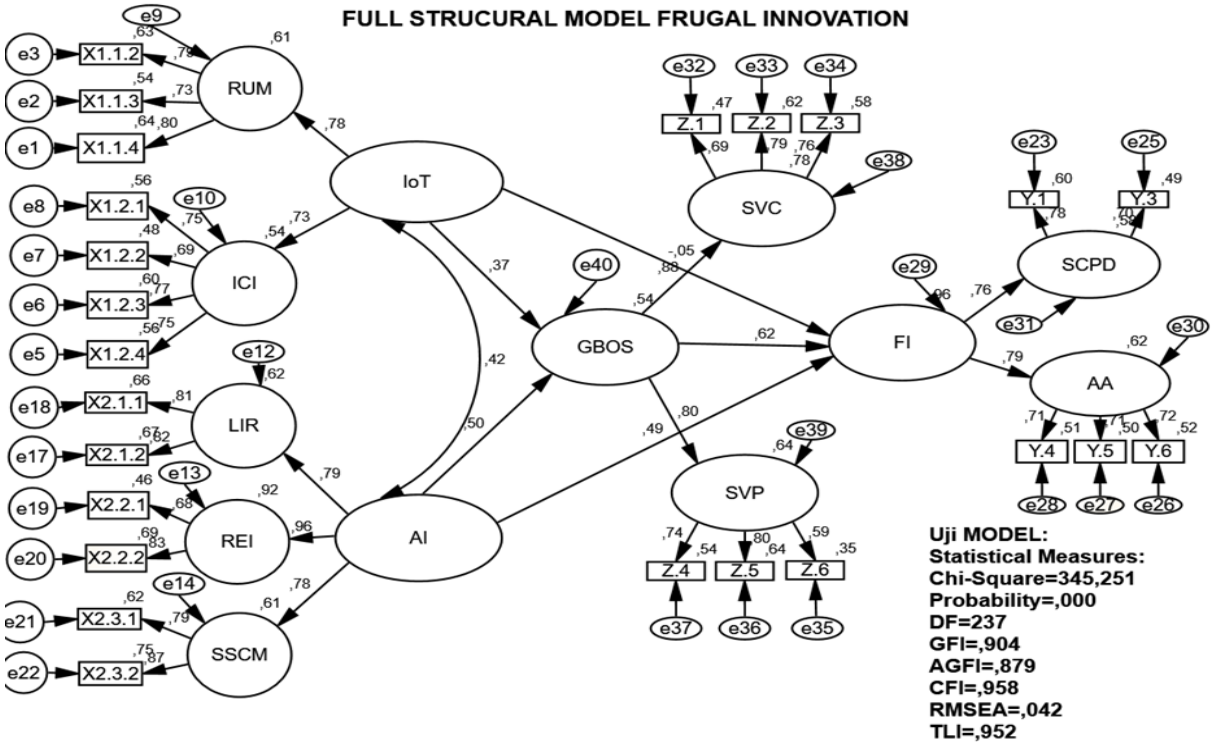

Figure 2. Full structural model – Frugal Innovation

Source: Output SEM-AMOS.

Mediation role testing

Through data processing results on the AMOS SEM path coefficient, which was studied by Baron and Kenny (1986), researcher looked at how GBOS affected the link between IoT and AI with FI. The successful outcome of mediation was assessed by analyzing the significant correlation between the independent and dependent variables. The results indicated no statistically significant correlation between IoT and FI ($\beta = 0.079$, $p = 0.646$). Therefore, Baron and Kenny (1986) criteria for their test were not fulfilled. The first mediating role of the indirect association between IoT and FI through GBOS was found to be statistically significant (P1: $\beta = 0.048$, $p < 0.001$) and (P2: $\beta = 0.456$, $p < 0.001$). Therefore, the initial mediation test proposed by Baron and Kenny (1986) was satisfied. GBOS served as a mediator in the link between the Internet of Things (IoT) and Financial Inclusion (FI). The indirect association of AI on FI through GBOS was found to have a statistically significant mediating impact. Specifically, the first path (P1: $\beta = 0.418$, $p < 0.001$) and the second path (P2: $\beta = 0.411$, $p < 0.001$) were both significant. Therefore, the second mediation test proposed by Baron and Kenny (1986) was successfully fulfilled. GBOS acted as a mediator in the relationship between AI and FI.

DISCUSSION

According to the study's findings, the empirical data does not support the initial hypothesis that the Internet of Things (IoT) would have a substantial adverse impact on frugal innovation. The observed effect was indeed negative, but it was not statistically significant. The outcomes of this study contradict prior studies, which indicated that IoT would enhance cost efficiency and improve time management (Jones & Graham, 2020; Widjaja & Gunawan, 2024), thereby significantly

facilitating frugal innovation. This study indicates that the utilization of IoT has a negative and negligible effect on frugal innovation. The initial cost of implementing IoT is significantly high for small and medium-sized enterprises (SMEs) in Indonesia. Alongside investing in the acquisition and development of technology, SMEs must also engage in ensuring their human resources are capable of operating it. Small and medium-sized firms encounter greater challenges when it comes to incurring the additional costs associated with skill enhancement and organizational changes required for the adoption and utilization of technology (Organisation for Economic Co-operation and Development, 2019). Jones and Graham (2020) asserted that several human resources lack an adequate understanding of the Internet of Things (IoT). This substantial investment is clearly inconsistent with the principle of frugal innovation, which seeks to develop cost-effective and efficient solutions for populations with constrained resources (Wooldridge, 2010), low cost (Dabić et al., 2022), and flexible-oriented (Fu et al., 2024). Secondly, not all SMEs are prompt in adopting IoT inside their operations. The insignificant impact of IoT on frugal innovation can be attributed to high implementation costs, which pose a barrier for MSMEs in resource-constrained contexts (Organisation for Economic Co-operation and Development, 2019). This finding suggests that while IoT has potential for cost-efficiency, its practical adoption among MSMEs is limited by additional costs related to technological acquisition and employee training.

Some researchers think that the manufacturing and industrial sectors are the primary and swiftest users of IoT technology (Cook, 2019; Varaniūtė et al., 2018). Artificial Intelligence (AI) may enhance frugal innovation by optimizing resource use and improving efficiency. The results of this study align with the conclusions of Qin (2024) research. Artificial intelligence (AI) revolutionizes creative endeavors, as evidenced Füller et al. (2022). Artificial intelligence (AI) enables the creation of economic, highly efficient, and user-focused solutions. Artificial intelligence enables the swift and extensive advancement of economics (Schwaeke et al., 2024). The ability of AI to analyze consumer patterns and behaviors allows innovators to discover new opportunities that adhere to the tenets of frugal innovation, which focuses on providing optimal value with few resources. The significant positive impact of AI on frugal innovation underscores its ability to optimize resource allocation and drive sustainable solutions. This study demonstrates that AI enables MSMEs to identify cost-saving opportunities through data-driven decision-making, aligning with the principles of frugal innovation. By leveraging AI, MSMEs can enhance their capacity for sustainable value creation, a key element of the Green Blue Ocean Strategy. Artificial intelligence facilitates the development of sustainable and economical solutions. The efficacy of AI use aligns with the emphasis on cost-effectiveness in frugal innovation. Besides efficiency, the elements affecting the ease of AI adoption in SMEs and its impact on innovation include the usability of AI, the advantages of AI implementation (Chatterjee et al., 2022), the effectiveness of digital transformation (Dörr et al., 2023), available resources, and managerial conduct (Korherr et al., 2023). Therefore, artificial intelligence (AI) has a significant role in enhancing the societal influence of frugal innovation, thereby increasing its accessibility to needy individuals.

This study discovered that the Internet of Things (IoT) has a beneficial influence on the Green Blue Ocean Strategy. This strategy focuses on ongoing innovation and value generation in unexplored areas, while also ensuring environmental equilibrium. The Internet of Things (IoT) enables firms to gather and analyze data instantly (Jeba & Rathi, 2021; Yu & Wang, 2022), leading to faster discovery of new prospects and the adoption of eco-friendly solutions (Almalki et al., 2023; Memić et al., 2022). Through IoT, MSMEs may oversee resource utilization in real-time, thereby minimizing waste and ineffective energy usage (Hariyani et al., 2024; Yen Ting et al., 2017). Furthermore, IoT empowers MSMEs to develop innovative eco-friendly goods (Almalki et al., 2023), including smart irrigation systems (Badrun & Manaf, 2021) and gadgets that use recycled materials. These technologies not only create new markets but also facilitate carbon footprint reduction and promote sustainable business practices. Conversely, IoT enhances transparency and consumer confidence for MSMEs by facilitating ecologically sustainable supply chain data tracking (Sallam et al., 2023). Consumers can access information on the provenance of raw materials, carbon emissions, or product recycling methods, therefore enhancing brand value among sustainability-conscious consumers. Moreover, IoT enhances logistics efficiency by improving distribution routes and reducing gasoline use. This not only reduces operational expenses but also enhances sustainability.

The findings of this study demonstrate that Artificial Intelligence (AI) has a substantial and beneficial influence on the execution of the Green Blue Ocean Strategy. Artificial intelligence is ideally suited to propel the Green Blue Ocean Strategy, facilitating the emergence of new chances for enterprises to establish uncontested market sectors and provide novel goods or services. Artificial intelligence may assist in identifying trends (Okeleke et al., 2024; Temitayo Oluwadamilola et al., 2024), identifying novel market possibilities (Mani, 2024; Perifanis & Kitsios, 2023), fostering value innovation (Perifanis & Kitsios, 2023), and surmounting entry obstacles, are all critical elements for the success of the Green Blue Ocean Strategy. AI plays a crucial role in assisting this approach by offering comprehensive and predictive data

analysis (GhorbanTanhaei et al., 2024), allowing organizations to find unexplored market potential and address customer demands with greener solutions. The integration of environmental peculiarities with novel market value characterizes this approach. The progress of artificial intelligence promotes environmental sustainability (Nastasa et al., 2024; Raman et al., 2024). By leveraging AI, firms may enhance production processes, minimize inefficiencies, and create new goods and services that not only align with the principles of sustainability but also adhere to the core principles of the Green Blue Ocean Strategy plan. This study contributes to our comprehension of how sophisticated technologies, such as artificial intelligence (AI), might enhance corporate strategies that prioritize sustainable innovation. These findings align with prior research indicating that AI has the potential to enhance operational efficiency and stimulate eco-friendly innovation.

This study illustrates that the adoption of the Green Blue Ocean Strategy positively influences frugal innovation. The Green Blue Ocean Strategy plan integrates the blue ocean strategy (Kim & Mauborgne, 2004) with the green ocean strategy (Hou, 2007). We integrate the two techniques to emphasize the cultivation of sustained value innovation. The Green Blue Ocean Strategy Approach substantially influences the promotion of frugal innovation in MSMEs by fostering the development of economic solutions that are both environmentally sustainable and inventive. The Green Blue Ocean Strategy can promote continuous innovation (Abdulkareem, 2022). This method prioritizes value innovation, which not only generates new goods or services but also minimizes expenses by removing superfluous elements or procedures. The Green Blue Ocean Strategy Approach facilitates MSMEs in optimizing local resource use and reducing waste within the framework of frugal innovation. For instance, MSMEs might diminish the utilization of costly raw materials by substituting them with more affordable and sustainable recycled resources, thus generating cost-effective solutions that align with the expanding green market. This study enhances existing research by illustrating the significance of the Green Blue Ocean Strategy as a vital driver for the progression of cost-efficient and sustainable innovation. This illustrates that a strategy focused on ambition and creativity benefits not just companies aiming to lead emerging sectors but also in promoting an effective method for innovation. The company will get a competitive advantage through the adoption of frugal innovation (Shahid et al., 2023).

The Green Blue Ocean Strategy facilitates the connection between the Internet of Things (IoT) and frugal innovation by integrating sophisticated technology with sustainability. The Internet of Things (IoT), which produces real-time data via sensors and connections (Soori et al., 2023), allows organizations to enhance operational efficiency and minimize resource wastage (Doniirawan, 2023). Nonetheless, the application of IoT frequently necessitates substantial expenditures. The Green Blue Ocean Strategy is pivotal in directing IoT implementation towards more economical, inclusive, and sustainable solutions. This method not only utilizes IoT for technical efficiency but also promotes social value and sustainability. Frugal innovation arises from the amalgamation of IoT and the Green Ocean Strategy. We utilize IoT data to create economical goods and services available to the broader community, especially in resource-limited settings (Nassani et al., 2022; Qin, 2024). This technique guarantees that the resultant innovation is both cost-effective and possesses a minimum environmental footprint, aligning with sustainability objectives.

This study demonstrates that the green ocean approach acts as a substantial mediator in the correlation between Artificial Intelligence (AI) and frugal innovation. AI facilitates frugal innovation by implementing the green ocean approach, which prioritizes sustainability and innovation in the exploration of undiscovered market prospects. Artificial intelligence (AI) allows firms to find cost-effective and environmentally friendly creative solutions (Bolón-Canedo et al., 2024). The blue ocean strategy provides a framework that promotes the production of new value (Kim & Mauborgne, 2004) by utilizing AI technology to develop goods and services that suit the changing demands of the market. These findings highlight the significance of implementing a green ocean strategy to integrate modern technologies like AI with cost-effective and environmentally friendly innovation approaches. The green ocean strategy serves as a mediator between AI and frugal innovation, enabling organizations to combine their sustainability objectives with inventive requirements that are adaptable to limited resources.

This study enhances the theoretical understanding of RBV by demonstrating how IoT and AI fulfill Valuable, Rare, Inimitable, Organized (VRIO) criteria, making them critical resources for achieving competitive advantages. Furthermore, GBOS introduces a novel perspective by integrating these technologies into a sustainability-driven framework, differentiating it from traditional BOS. This positions GBOS as a dynamic capability that allows SMEs to adapt to market demands while maintaining ecological balance, a contribution that expands the applicability of RBV in sustainable innovation research. The mediation role of GBOS highlights its function as a strategic framework that integrates sustainability into innovation processes, enabling MSMEs to leverage IoT and AI effectively. This finding contributes to the Resource-Based View (RBV) by emphasizing GBOS as a unique organizational capability that aligns

with the VRIO framework—valuable, rare, inimitable, and organized resources (Barney, 1991; Barney & Clark, 2007). By embedding sustainability principles, GBOS offers a practical extension to RBV, addressing the dynamic demands of resource-constrained environments (Teece et al., 1997). The Internet of Things facilitates real-time resource management, while artificial intelligence enhances corporate process optimization and predictive analytics. Both technologies satisfy the RBV criteria as valuable, rare, inimitable, and well-structured resources that underpin durable competitive advantages. Nonetheless, the deployment of IoT and AI necessitates considerable upfront investment, particularly in the enhancement of human resource competencies. Consequently, SMEs must enhance their organizational ability to proficiently manage and leverage these technologies as an integral component of a resource-based strategy. Furthermore, the use of these technologies underscores the need for dynamic capability within the Resource-Based View (RBV), necessitating that SMEs consistently adjust and reorganize their resources to remain pertinent amid market fluctuations. The capacity to leverage real-time data from IoT enhances operational efficiency, while AI's capability to comprehend customer behavior enables SMEs to develop goods and services that align more closely with market demands. This indicates that investment in technological advancement and associated human competencies is not only a reaction to immediate demands but also a strategic approach to sustain competitiveness in a more intricate market.

This study demonstrates that, within the Green Blue Ocean Strategy (GBOS) framework, the integration of IoT and AI allows SMEs to generate sustainable value ideas and access new markets. The Internet of Things (IoT) assists small and medium-sized enterprises (SMEs) in minimizing resource waste via real-time monitoring, aligning with the sustainability tenets of the green ocean strategy. Simultaneously, AI enables the identification of unexploited market possibilities and the development of creative solutions that are more efficient and ecologically sustainable. This strategy not only generates competitive benefits but also assists organizations in fulfilling customer requests for more ecologically sustainable business operations. Moreover, GBOS advocates for SMEs to develop products and services that are both pertinent to market demands and possess a small ecological footprint. By utilizing AI, SMEs may create goods that include recycled materials or minimize energy usage, thereby generating new value in a competitive marketplace. This approach emphasizes that sustainability and innovation don't have to conflict; they can combine to create relevant, economical, and significant solutions. Consequently, GBOS functions as a proficient framework for SMEs to not only endure but also thrive against market fluctuations and worldwide environmental adversities.

CONCLUSION

This study extends the Resource-Based View (RBV) by demonstrating how IoT and AI can serve as strategic resources that fulfill the VRIO criteria, driving frugal innovation in resource-constrained environments. Furthermore, the Green Blue Ocean Strategy (GBOS) framework highlights the integration of sustainability into innovation processes, enabling businesses to achieve economic growth while reducing ecological footprints. By extending the application of the Resource-Based View (RBV) theory, this study demonstrates how integrating IoT and AI can promote frugal innovation strategies that drive both economic efficiency and ecological sustainability in Asian developing markets. The findings indicate that leveraging AI significantly enhances energy efficiency (factor loading 0.833), while IoT contributes to sustainable innovation, albeit with challenges in infrastructure and data management. The study's hypothesis testing yields theoretical and practical implications for Asian businesses. The researcher enhances our comprehension of the blue ocean strategy's function by utilizing the theoretical implications of the RBV theory approach. RBV theory views the GBOS concept as having theoretical implications, such as leveraging the company's unique and difficult-to-replicate internal resources, acquiring company resources at a cost lower than their potential value, and creating economic value for the company while maintaining resource scarcity. This research enriches the existing literature by demonstrating that combining the RBV framework with GBOS provides a robust approach for leveraging technology-driven sustainable innovation, thus enhancing competitive advantages in resource-scarce environments.

The RBV theoretical perspective addresses the following questions in the study's findings: First, by utilizing economic innovation efforts from the highest factor loading of 0.833, it shows that AI can be used to maximize energy in operations. However, IoT facilities must aid in optimizing cost-effective innovation despite organizational, business, and technical hurdles. Furthermore, only a few companies have the necessary infrastructure and technology to optimize data management and collection. Second, the GBOS solution can directly or indirectly foster economic innovation by fusing AI and IoT with environmentally friendly, sustainable innovation components. By establishing guidelines for the use of ecologically friendly technical raw materials to boost resource efficiency, GBOS broadens scientists' and marketing professionals'

understanding of BOS, allowing them to focus on sustainable value development. Third, actors in Asia's creative economy can benefit practically from the role of GBOS. The theoretical implications emphasize the synergy between GBOS and RBV in fostering sustainable innovation, particularly in cost-constrained contexts. From a managerial perspective, this study provides actionable insights for businesses in adopting IoT and AI to improve resource efficiency and achieve competitive advantages. Socially, the application of frugal innovation through GBOS enables inclusive economic growth by promoting eco-friendly and culturally significant products, addressing the growing demand for sustainable practices in developing regions. Traditional goods or regional services can offer distinctive products that introduce the history of regional Asian goods and open up new markets to the outside world. The sustainable demand for inventive, ecologically friendly products is driven by Asia's rapid economic growth. Innovative enterprises in Asia's developing nations can achieve cost savings in operations through the application of technology in GBOS. Additionally, GBOS is proactive in developing improvements to environmentally friendly technology innovation policies and promotes environmentally friendly regulatory changes.

In a circular economy framework, the integration of parsimonious innovation practices generates value by facilitating the exchange of knowledge and innovation capability (Yousaf et al., 2022). This study provides actionable insights for business managers in developing regions. By adopting low-cost IoT and AI technologies, firms can enhance their resource efficiency and reduce operational costs. Additionally, the GBOS framework offers a pathway for creative industries to penetrate new markets by promoting sustainable, culturally significant products. The adoption of frugal innovation practices through GBOS can support community-driven enterprises by promoting the use of affordable technologies, thereby contributing to inclusive economic growth and sustainable development. Frugal innovations, which are typically low-cost and practical solutions that emerge from contexts of institutional vacancies and resource constraints, involve the creative use of existing resources (Manta et al., 2021). Adopting low-cost innovation methods helps build long-lasting business management skills and abilities in uncertain situations. Creative industry companies can support innovation and make necessary changes to their structure and business technologies by working with internal and external stakeholders, enhancing creative thinking skills, and upgrading and integrating business technologies. Policymakers are encouraged to support regulatory frameworks that incentivize the use of eco-friendly technologies and foster strategic partnerships between industries to drive frugal innovation.

The contextual scope of this investigation is restricted in several ways. The empirical results were exclusively obtained from Central Java, Indonesia, which is still classified as a developing Asian country. This study's empirical scope is limited to Central Java, which may restrict the generalizability of the findings to more developed regions. Additionally, the cross-sectional design limits the understanding of long-term impacts of IoT and AI adoption on sustainable innovation. Consequently, the findings cannot be applied to developed countries. Unlike a longitudinal study, the data collection procedure was conducted cross-sectionally within a limited timeframe. However, these findings highlight the necessity of conducting additional research on AI applications in other industries, emphasizing the importance of this study in the broader context of AI and innovation. As a result of these constraints, future researchers may apply network theory or strategic partnership theory to further develop the results of this study in various business contexts. This may entail creating concepts related to green innovation partnerships, sustainable innovation orchestration, and green value adaptability. Future research should adopt longitudinal designs to assess the evolving impact of IoT and AI on sustainability in diverse economic contexts. Additionally, integrating network theory and strategic partnership frameworks could enhance the applicability of GBOS across various sectors, including healthcare and logistics. Exploring green innovation partnerships and sustainable orchestration strategies will further expand the understanding of GBOS in promoting cost-effective, eco-friendly solutions. Expanding the data from this study will provide valuable insights for marketing scientists, business proprietors, and marketing managers in the development of sustainable, eco-friendly product innovation strategies.

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Author contributions statement

Diana Aqmala: Conceptualization, Funding Acquisition, Supervision, Validation. **Roymon Panjaitan**: Conceptualization, Methodology, Writing – Original Draft, Writing – Review & Editing. **Elia Ardyan**: Data Curation, Formal Analysis, Software, Visualization. **Febrianur Ibnu Fitroh Sukono Putra**: Data Curation, Investigation, Project Administration, Resources.

Conflicts of interest

The authors have no conflict of interest to declare.

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The impact of eco-innovation on circular economy in EU countries: How patents affect circular material use rate?

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Abstract

PURPOSE*: The main objective of this study is to examine how eco-innovation activities, measured by the number of patents related to recycling and secondary raw materials, affect the level of use of circular materials in economic processes in European Union countries. Simultaneously, to take into account the impact of the other drivers of the circular economy, the study includes control variables such as GDP per capita, share of income from environmental taxes, age structure of the population, and level of education of the population.* **METHODOLOGY***: This study uses a generalized linear model for panel data. For all analyzed explanatory variables, greater inter-group variation than intra-group variation was observed, so a panel-averaged effects estimator was used. The study sample includes 28 European Union (EU) countries. The time scope of this study is 2010-2019. Eurostat database was the source of the unbalanced panel data. This study seeks answers to the following research question: What is the impact of patents related to waste management and recycling on the circularity rate of the EU economies?* **FINDINGS***: The results indicate that leaders in the area of circularity are the Netherlands, France, and Belgium. Ireland, Romania, and Portugal occupy last place in terms of the circularity of the economy. There is considerable variation in the number of patent applications related to waste management and recycling in the EU countries. Luxembourg, Finland, Belgium, and the Netherlands have the highest propensity for patents. In contrast, Bulgaria, Greece, and Croatia show the lowest patent activity. Finally, the higher the propensity to patent in waste management and recycling technologies, the higher the rate of circular use of materials.* **IMPLICATIONS:** *The results provide a compelling rationale for prioritizing and incentivizing investments in promising technologies to achieve both environmental sustainability and economic prosperity in the long term.* **ORIGINALITY AND VALUE***: Our study sheds new light on the link between eco-innovation and circular economy in EU countries. We address the issue of possible nonlinearities between circularity and its drivers. Given the fractional nature of the response variable (i.e., circular material use rate), we apply the generalized estimating equations (GEE) approach to model both the mean structure and association structure of fractional responses.*

Keywords: *circular economy, CE, circularity, eco-innovation, patent, circular material use, CE driver, EU countries, generalized estimating equations, recycling technologies, waste management*

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INTRODUCTION

The concept of the circular economy (CE) has been documented in scientific literature since the late 1960s (Boulding, 1966). However, the practical implementation and refinement of its basic principles began in the early 21st century. Initially, this took place in Asian countries, such as China and Japan, and then, as recommended in European Commission publications since 2014, in many European Union member states (Kulczycka, 2019). This concept has attracted increasing attention from policymakers, the scientific community, and economic practitioners alike (Ellen MacArthur Foundation, 2012; 2015, 2016; European Commission, 2015; 2020; Kirchherr et al., 2017; 2019; 2023a,b).

As each makes a distinct contribution to the development and use of the circular economy (CE), China and Japan are undoubtedly its pioneers. According to Arai et al. (2024), Japan is a pioneer in the adoption of CE policies, especially with regard to the Sound Material-Cycle Society, which prioritizes new technology over social justice considerations. China, on the other hand, has shown a significant increase in pilot projects and a top-down approach to resource management since incorporating CE into its political framework throughout the 1990s (Nemesh, 2022). Both nations have developed sizable frameworks for CE, with China emphasizing industrial applications and stakeholder involvement (Ogunmakinde, 2019) and Japan leading the way in end-of-life vehicle recycling with sophisticated legislation (Wang et al., 2021).

The European Commission's adoption of a new roadmap for a circular economy marks an important milestone in the implementation of the European Green Deal (European Commission 2019), a comprehensive strategy to achieve sustainable growth in Europe. This action plan includes various initiatives covering the entire product lifecycle. In particular, it focuses on aspects such as product design, promoting closed-loop economy processes, encouraging sustainable consumption, and maximising resource retention in the EU economy (European Commission, 2020).

Over the past decade, the number of publications on circular economic issues has increased significantly. The thematic scope of these studies mainly focused on the following:

- the essence and genesis of the CE concept (Kirchherr et al., 2017, 2019, 2023a,b; Prieto-Sandoval et al., 2018; Maksymiv et al., 2021; Gonçalves Castro et al., 2022);
- comparisons and relations of the circular economy with other concepts of socioeconomic development (Panchal et al., 2021; Triguero et al., 2021; Mirzyńska et al., 2021; Skvarciany et al., 2021; Santeramo, 2022; Sulich & Soloducho-Pelc, 2022; Simionescu, 2023);
- barriers and determinants of CE implementation (The Routledge Handbook of..., 2024; Munaro & Tavares, 2023; Aarikka-Stenroos et al., 2023; De Pascale et al., 2023; Thi-Kieu Ho et al, 2023; Neves & Marques, 2022; Arranz et al., 2022; Chiaroni et al., 2022; Hina et al., 2022; Kostakis & Tsagarakis, 2022; Tan et al., 2022; Harta et al., 2019);
- planning issues, including the formulation of CE development strategies at various governance levels (European Commission, 2015, 2020; Vanhamäki et al., 2021; Hartley, 2023; Purvis et al., 2023; Uvarova et al., 2023);
- promotion of good practices and models for circular economy implementation (Kopnina, 2019; van Langen & Passaro, 2021; Melles, 2023; Lisiecki et al., 2023; The Routledge Handbook of..., 2024;
- methods and evaluation of the effects of CE implementation (D'Adamo et al., 2024b; Banjerdpaiboon & Limleamthong, 2023; De Pascale et al., 2023; Matos et al., 2023; Kulczycka, 2020; Fura et al., 2020; Kasztelan, 2020; Moragaa et al., 2019; Palea et al., 2023).

One of the important areas of scientific interest remains issues related to the impact of eco-innovation (EI) on the dynamics of the processes of implementing the assumptions of the circular economy (Frone, 2017; Vence & Pereira, 2019; De Jesus et al., 2019; Stankevičienė & Nikanorova, 2020; Cainelli et al., 2020; Gomonov, 2021; Khaertdinova, 2021; Bucea-Manea-Tonis et al., 2021; Lehmann, 2022; Khan, 2022; Pichlak & Szromek, 2022; Platon et al., 2022;2023; Boonman et al., 2023; Rosca-Sadurschi & Șeremet (Ceclu), 2023; Bao et al., 2023). The correlation between CE and EI is readily apparent and it is doubtful that CE can be accomplished independently. However, the precise intricacies of this relationship need to be established. Not every aspect of EI is linked to CE, as not every aspect of CE necessitates innovation. Nevertheless, there is some overlap between the two. More specifically, in order to attain resource efficiency and minimize waste, there is a requirement for innovative waste management technologies (Cramer, 2015; Ghisellini et al., 2016; Lang-Koetz et al., 2010). These technological advancements should enable greater recyclability, thereby resulting in reduced waste compared with the current linear model of take, make, and disposal (Ness, 2008). Regrettably, the double externality predicament associated with the circumstance in which the entire society reaps the benefits of environmental innovation, while a solitary company bears all the costs independently (Rennings & Ziegler, 2004; Beise & Rennings, 2005), diminishes the motivations for corporations

to invest in such technologies. It is important to acknowledge that safeguarding inventions in the realm of waste management technologies and recycling by obtaining patents may offer economic inducements for corporations to commercialize their innovations (Habib et al., 2019). Conversely, there is a conflict between the rights of the patent holder and the necessity to utilize their environmentally friendly technology, which can be characterized as the "Green Patent Paradox," whereby patented technologies designed to mitigate the ramifications of climate change or replace environmentally hazardous industries may not realise their full potential partly due to patentees refraining from licensing their products (Cayton, 2020). Although green technology litigations are infrequent, Khan and Singh (2023) provide examples of crucial green technology litigations that underpin the patentability and granting of compulsory licensing of green technologies. They also analyze the link between green patenting and ESG practices. The latter are supposed to motivate firms to engage in green patent applications (Wang et al., 2023) and may provide useful information for professional and non-professional ESG investors (Škapa et al., 2022).

Achieving the goals of a circular economy requires significant technological and organizational changes. Simultaneously, to ensure the effective operation of circular economy models, it is necessary to use a systems approach to understand the impact of multiple interrelated factors that have different correlations and are constantly changing. Various elements of the system should be evaluated simultaneously.

Considering the above, the main objective of this study is to examine how eco-innovation activities, measured by the number of patents related to recycling and secondary raw materials, affect the level of use of circular materials in economic processes in European Union countries. Simultaneously, to take into account the impact of the other drivers of the circular economy, the study includes control variables such as GDP per capita, share of income from environmental taxes, age structure of the population, and level of education of the population.

The remainder of this paper is organized as follows. The Introduction section discusses the subject matter investigated. Subsequently, the Theoretical Background imparts a plethora of fruitful notions pertaining to the circular economy and its drivers. The sections concerning the Research Method disclose the provenance of the data and statistical methodologies employed in the research. The Results and Discussion section presents the outcomes and deliberates on the findings of previous studies, along with the unique perspectives acquired from the research results. Finally, the Conclusion section provides a concise summary of the findings.

THEORETICAL BACKGROUND

The concept of circular economy

In 2023, a group of scholars gathered around Kircherr (2023a), analyzed 221 definitions of the circular economy and formulated specific conclusions. First, it involves both consolidation and diversification. Second, definitional trends have emerged as potentially more relevant to science than to practice. Third, researchers are increasingly recommending fundamental systemic changes to enable CE, particularly within supply chains. Fourth, sustainability is often considered a central goal of CE, but uncertainty persists regarding whether CE can simultaneously promote both environmental and economic sustainability. Finally, recent research has shown that CE transformation relies on a broad alliance of stakeholders, including producers, consumers, policymakers, and researchers.

The most commonly cited definition of CE is that of the Ellen MacArthur Foundation (Kulczycka, 2019) – 'A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models' (Ellen MacArthur Foundation, 2012).

Kircherr et al. (2017) define CE as a peculiar economic system, pointing out that it operates at the micro (products, companies, consumers), meso (eco-industrial parks) and macro (city, region, nation, and beyond) levels, aiming to achieve sustainable development, thereby simultaneously creating environmental quality, economic prosperity, and social justice, for the benefit of current and future generations.

In comparison, the viewpoint platform Circular Academy perceives CE as an economic model that fundamentally alters the way production and consumption occur. Taking cues from the principles governing ecosystems and propelled by a design that aims to restore, this revolutionary system strengthens adaptability, eliminates inefficiency, and encourages the generation of mutually beneficial outcomes through an intensified circulation of both tangible and intangible streams (Circular Academy, 2023).

The European Commission, in its 2015 Roadmap for a Circular Economy (European Commission, 2015), instead states that the transition to a closed-loop economy, which aims to preserve the value of products, materials, and resources in the economic system for a longer period while minimizing the generation of waste, is a major undertaking by the European Union for a sustainable, low-carbon, energy-efficient, and competitive economy. Meanwhile, the 2020 revision of the document states that the European Union (EU) must expedite the process of transitioning towards a regenerative growth model that emphasizes returning more to the planet than it extracts. Additionally, it should actively work towards maintaining resource consumption within the limits of the planetary boundaries. Consequently, the EU should endeavor to diminish its consumption footprint and increase its circular material utilization rate twofold in the forthcoming decade (European Commission 2020).

Current definitions cover a wide range of explanations as to whether they address resource allocation (such as waste reduction and renewable energy) or economic aspects (such as transformative, regenerative, and value-creating economies). Although some definitions delve into combining circularity with a completely innovative approach to defining the economy, the basic concepts of these definitions focus exclusively on the circulation of resources and materials, thus allowing for further interpretation of the new regenerative economy.

Eco-innovation for circular economy

The term eco-innovation is used to categorize innovations that lead to a sustainable environment through the development and introduction of ecological enhancements (Kemp & Foxon, 2007). Reid and Miedzinski (2008) define eco-innovation with more precision. The latter needs to be linked to environmental issues, such as recycling and reuse. From an economic point of view, the most important peculiarity of eco-innovation is the so-called double externality problem. This problem is reflected by the fact that eco-innovations generate positive spillovers, that is, knowledge externalities and externalities related to positive effects on the environment. Both externalities cause suboptimal investments in eco-innovations (Losacker et al., 2023). This justifies the application of policy instruments (technology-push and demand-pull types) to provide the socially required level of investment in eco-innovation. Moreover, the double-externality problem may evolve into an appropriability problem because firms that introduce eco-innovations may experience difficulties benefiting from their generation. Ensuring the appropriability of profits from eco-innovations is possible thanks to secrecy, lead time, confidentiality agreements, complexity, and the intellectual property rights system, which includes patents granted for novel, non-obvious, and useful inventions.

Patents are a good means to measure eco-innovation. Patents are the exclusive monopoly rights granted to the owner of the invention. The number of patents related to environmental technologies (green patents) is often used to study both the innovative output and level of eco-inventive activities in particular technological fields (Oltra et al., 2010). Green patents are granted on technologies relating to waste, wind power, geothermal energy, solar energy, tidal energy, etc. (Khan & Singh, 2023). Favot et al. (2023) mention three approaches available to identify green patents based on the code classification: IPC Green Inventory, ENV-TECH, and Y02/Y04S Tagging scheme. From a CE perspective, within the green patents category, circular patents are most commonly identifiable as patents related to the main technological inventions for closing material loops, such as recycling and the application of secondary raw materials (Portillo-Tarragona et al., 2024).

Measuring eco-innovation is important for analyzing the economic and environmental consequences of green products and technologies. As suggested by Urbaniec et al. (2021), the neoclassical perspective seems particularly relevant for analyzing the role of eco-innovation in the economy when technological change is claimed to be an important source of development. Using this approach, eco-innovations are expected to lead to sustainable development owing to their contribution to technical progress, resulting in more efficient and responsible use of natural resources. R. Solow, one of the most important scholars of the "Neo-Classic Economics School", states that the authors load their case by letting some things grow exponentially, while others do not. Population, capital, and pollution grow exponentially in all models, but technologies for expanding resources and controlling pollution are permitted to grow, if at all, in discrete increments (Pansera, 2011, p.129). Within the neoclassical framework, pollution and environmental degradation result from externalized costs of industrial processes that can be minimized by eco-innovation. A prerequisite for such an influence of eco-innovation is a free market mechanism with environmental regulations to adjust for market failures. In this spirit, eco-innovation is regarded as a useful means to reenergize the sluggish economic growth of industrialized countries. In general, the impact of eco-innovation on industrial processes and consumption in the economy refers to three dimensions: energy, waste, and materials. The last two dimensions are extremely important from the CE perspective.

In a more general context, the scientific community agrees that eco-innovation is a basic condition for the development of a circular economy. Prieto-Sandoval et al. (2018) emphasize the significance of eco-innovations as a means of establishing a circular economy. They contend that comprehending eco-innovation from an ecological-centred viewpoint is essential for ensuring the practicality and prosperity of CE. Vence and Pereira (2018) indicate that eco-innovation plays a crucial role in driving the transition to a circular economy, with both technological and non-technological innovations being key. Similar conclusions are drawn by Pichlak and Szromek (2022), who indicate that eco-innovation, both technological and non-technological, acts as a catalyst for a circular economy. D'Adamo et al. (2024), on the other hand, find that technology plays a critical role in enabling an efficient closed-loop municipal waste management strategy that minimizes landfilling and other environmentally detrimental activities. By contrast, Cainelli et al. (2020) believe that environmental policy and green demand drivers are significant in promoting resource efficiency-oriented eco-innovations. Frone (2017) presents a study in which the strategic role of eco-innovation parks in promoting a circular economy is highlighted, particularly in the context of industrial synergy and regional metabolism. Edeh and Vinces (2023) study how different external sources of knowledge influence eco-innovation of small and medium-sized enterprises (SMEs) in developing economies. Their investigation reveals that the influence of outside information on eco-innovation differs and isn't always advantageous for businesses. Eco-product and eco-process innovation are strongly correlated with external knowledge from suppliers. On the other hand, eco-product innovation is favorably correlated with external consumer knowledge, but not with eco-process innovation. Horizontally, rival companies' external knowledge fosters eco-process innovation but not eco-product innovation.

It should be noted that eco-innovation contributes significantly to the development of circular economies in EU countries. This leads to progress toward sustainability by reducing the environmental impact of production, increasing resilience to environmental pressures, and promoting efficient use of natural resources (Rosca-Sadurschi & Șeremet (Ceclu), 2023). Gomonov's (2021) analysis confirms the importance of eco-innovation for CE in EU countries. The results show that the level of eco-innovation implementation varies across EU countries. Denmark and Sweden have emerged as unequivocal frontrunners, while Bulgaria, Cyprus, and Poland are making significant strides in catching up. Stankevičienė and Nikanorova (2020) propose the concept of measuring the development of eco-innovations in the context of the circular economy, with a focus on recycling, circular material usage, material efficiency, and waste management. Based on their analysis of the Baltic Sea region, the leaders in the eco-innovation ranking are Sweden, Denmark, and Germany, while Latvia, Estonia, and Poland are at the bottom of the pile. Technological and financial capabilities are essential drivers for all types of closed-loop economic activities in European companies, and public support is particularly important for recycling and process redesign (Triguero et al., 2021). Based on Platon et al. (2022, 2023), innovation in EU member states has a moderate and lagging effect on recycling. Eurozone membership has a positive impact on recycling and the circular economy. Eco-innovation and recycling play an important role in reducing the material footprint per capita and should be at the center of policies aimed at decoupling economic growth from raw material consumption. In the long run, by promoting eco-innovation and recycling, countries will minimize their demand for and consumption of raw materials.

Andre et al. (2015) find that the industry is closing the loop for some metals, and recycling-related patents play a significant role in influencing the use of closed-loop materials. Additionally, patents are seen as tools for new technologies in the transition to a circular economy, promoting advanced technologies, sustainability, and inventive activity (Khaertdinova et al., 2018; Khaertdinova et al., 2021). They contribute to the creation of new business opportunities and the development of circular economic centers. Recycling-related patents drive innovation and technological progress, supporting the transition to a closed-loop economy and sustainable use of materials (Jaakkola, 2019; Kostakis & Tsagarakis, 2022). Dume et al. (2022), in turn, emphasize that the selection and engineering of materials is a critical component towards the development of a circular economy model. Circular materials require a deliberate design that facilitates the full recycling of materials and innovative synthesis approaches that avoid the utilization of toxic precursors or the creation of undesirable by-products to restore the raw materials. Emphasizing more intelligent designs and conducting comprehensive analyses of the life cycle will shed light on the potential impact of circular material design on the development of a circular economy.

Based on these considerations, we formulate the following hypothesis: Eco-innovation, measured by patents related to recycling and secondary raw materials, has a positive impact on the circularity of EU countries.

Other drivers of circular economy

The process of implementing a circular economy depends on several conditions of different nature. The literature suggests the need to include economic and social factors in the analysis of the impact of patents related to recycling and secondary

raw materials on the use of circular materials in economic processes. These factors include GDP per capita, share of income from environmental taxes, age structure of the population, and level of education of the population.

Many scientific studies assume a positive relationship between GDP and the circular material use rate. Škare et al. (2023) find that income inequality is a barrier to circular economic development, indicating that higher GDP levels may be associated with higher circular material use rates. Kostakis and Tsagarakis (2022) also state that economic wealth positively affects material recycling and circularity rates. Grdić et al. (2020) conclude that the application of the circular economy concept can ensure economic growth and GDP growth while reducing the use of natural resources. On the other hand, Vuță et al. (2018) show that measures associated with the circular economy, such as the recycling rate of municipal waste and research and innovation expenditure, have positive effects on resource productivity and economic growth. In summary, these studies suggest that higher GDP levels are associated with increased circular material use rates. Wu et al. (2019), in turn, find that the GDP level has a significant impact on the rate of closed-loop material use. In general, the relationship between the GDP level and the rate of closed-loop material use is influenced by the principles of the closed-loop economy and the dynamics of economic cycles. However, one study by Pothen and Welsch (2019) suggests that there is a positive relationship between GDP per capita and material use, but this relationship becomes insignificant when endogeneity and nonstationarity are taken into account.

Another control variable is the share of income from environmental taxes. Environmental taxes, such as those imposed on incineration and landfills, have been found to have a beneficial influence on the utilization of circular materials by mitigating environmental repercussions and stimulating the practices of utilisation and recycling, thereby fostering a circular economy (Freire-González et al., 2022). This assertion is further corroborated by Kostakis and Tsagarakis (2022), who discern a positive correlation between the magnitude of environmental taxes and the recycling of materials as well as the level of circularity. Nevertheless, the efficacy of these levies may fluctuate contingent upon their formulation and implementation, as underscored by Walker et al. (2020), within the confines of a plastic levy. Aziz (2021) suggests that while the relationship between taxes and the circular economy is not consistent, there is a tenuous connection. Ojha and Vrat (2020) underscore the necessity of a transition from a linear model of resource consumption to a circular one, a transformation that could be expedited by environmental taxes.

The age structure of a population can significantly impact a circular economy in various ways. Struk and Soukopova (2016) investigate the correlation between the age composition of individuals residing in Czech municipalities, their per capita production of municipal solid waste, and their individual levels of waste separation. This study reveals that individuals in younger age brackets demonstrate superior performance in both dimensions. Conversely, individuals between the ages of 50 and 79 years exhibited the highest per capita production of residual waste and displayed the lowest levels of waste separation. Rybová and Slavík (2017) demonstrate that the generation of plastic waste is influenced by socio-demographic factors such as age. Ottelin et al. (2020) note that diverse household types encompassing varying age compositions manifest distinct patterns of circular consumption. Nevertheless, the association between these patterns and the overall material footprint may be tenuous, owing to the occurrence of rebound effects.

The last control variable included in the analysis is the population's level of education. Some studies collectively suggest that educational level has an impact on circular material use. Marouli (2016) emphasizes the need for education to promote circular and systemic thinking to achieve a circular economy and reduce waste generation behaviors. Pelău and Chinie (2018) find that a higher level of education positively influences the recycling rate of waste in an economy. Additionally, Kopnina (2019) highlights the importance of incorporating circular economy principles into business education to address the challenges of sustainable production. Finally, Ramli et al. (2021) discuss the need for students in higher education to adopt a circular economy approach in recycling and reusing study materials, indicating that technology can play a role in facilitating these practices. The level of education has an impact on circular material use. Higher education, such as a college degree, is associated with pro-environmental behaviours, including recycling (Loomis, 2020). Additionally, education can influence individuals' knowledge of conservation strategies and willingness to engage in environmentally friendly actions (Méndez-Giménez et al., 2012).

RESEARCH METHOD

We employ a generalized linear model to assess the effect of eco-innovation activities on the use of circular materials in economic processes in European Union countries. The level of use of circular materials is measured using the circular material use rate. The indicator is calculated as the share of material recycled and fed back into the economy, thus saving

the extraction of primary raw materials in overall material use. We apply eco-innovation activities, measured by the number of patents related to recycling and secondary raw materials, as the key explanatory variable. The other drivers of the circular economy serve as the control variables. These include GDP per capita, the share of income from environmental taxes, the age structure of the population, and the level of education of the population. Table 1 presents the responses and the explanatory variables used in the model.

The sample consists of 28 European Union countries (Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom) from 2010 to 2019. As determined by the availability of data in the Eurostat Database, we deal with an unbalanced data set. Relying on a single data source avoids the potential issues related to data comparability. The choice of the generalized linear panel data model to assess the effect of eco-innovation activities on the use of circular materials in economic processes in European Union countries results from the nature of the response variable. The application of the fractional response variable arises with functional form issues. The logit and probit models are the most commonly used tools for fractional response variables. We use the generalized estimating equations (GEE) approach to model both the mean structure and association structure of fractional responses.

Table 1. Response and explanatory variables

No .	Variable name	Measurement	Symbol
Response variable			
1.	Circular materials use	Ratio of the circular use of materials to the overall material use	CIR
Explanatory variables			
2.	Patents	Number of patents related to recycling and secondary raw materials per million inhabitants	PAT
3.	GDP per capita	GDP per capita (in PPS_EU27 from 2020 = 100)	GDP
4.	Education level	Pupils and students having Bachelor's or equivalent level as % of total age population	EDU
5.	Total environmental taxes	Proportion of environmental tax revenues in total revenues from all taxes	TET
6.	Old-age-dependency ratio	Ratio between number of persons aged 65 and over and number of persons aged between 15 and 64	OAD

GEE is a method developed by Liang and Zeger (1986) for estimating the parameters of generalised linear models, which are also known as population-averaged panel-data models. It offers a robust approach for accounting for dependencies among observations within a dataset. GEE adopts a quasi-likelihood approach, focusing on estimating the average population parameters, and does not require complete specification of the joint distribution of the data, making it less sensitive to distributional assumptions and robust to misspecifications.

We have available t observations, $t = 1, 2, \ldots, T$, for each subject i, $i = 1, 2, \ldots, N$. The response variable was y_{it}, $0 \leq y_{it} \leq 1$, and the outcomes at the endpoints were zero and one. The explanatory variables were included in a 1 x K vector, $\mathbf{x}_{it}$. For the mean response, the generalized linear model is specified as follows: , i -= 1, 2, …, N; t = 1, 2, …, T, where g() denotes the link function. The GEE method accommodates a wide range of models by allowing flexibility in the specification of the dependent variable distribution and the choice of the link function. For a normally distributed dependent variable y_{it} and an identity link function, the model reduces to linear regression. When y_{it} follows a Bernoulli distribution with a logit link function, the result is logistic regression. Similarly, for y_{it} with a Poisson distribution and a natural log link function, the model corresponds to Poisson regression, also known as a log-linear model. If y_{it} is a fractional variable, as in our case, an appropriate choice of g() is either a logit or probit function.

The GEE procedure declares the within-group correlation structure, reflecting the assumed dependence among observations in the correlation matrix. Common choices include exchangeable, autoregressive, and unstructured correlations. The exchangeable correlation structure assumes that the correlation between any two observations within the same individual is constant, irrespective of the time points at which the observations are recorded. This implies that all off-diagonal elements of the correlation matrix are equal, while the diagonal elements are fixed at one. The autoregressive correlation structure assumes that the correlation between two observations is a function of their lag and it decreases as the time between them increases. The unstructured correlations make no specific assumptions about the pattern of correlations, allowing each pair of observations to have a unique correlation. While highly flexible, this approach can be computationally

intensive and may require a large sample size to estimate the numerous correlation parameters reliably. GEE estimation involves iteratively estimating model parameters using a sandwich estimator to account for within-cluster correlations.

RESULTS AND DISCUSSION

Following the procedure described in the previous section, we identified the key factors determining the development of circular materials in economic processes. Table 2 presents the descriptive statistics of the variables used in the survey and the panel decomposition of their standard deviations. The average circular use of materials in the 25 EU countries increased from 8.2% in 2010 to 9.7% in 2019. The lowest average levels of this indicator were observed in Ireland (1.8%), Romania (2.1%), and Portugal (2.1%). In turn, the highest average values of the indicators were in the Netherlands (27.3%), France (18.3%), and Belgium (18.1%). It should be noted that our results are generally in line with those of other studies that use a circular economy index to measure the progress of European countries in their transition towards CE. For example, Mazur-Wierzbicka (2021) finds evidence of a two-speed Europe in relation to the advancement of European Union member states in pursuing operations according to CE principles. The countries with the highest CE index values include Germany, Belgium, Spain, France, Italy, and the Netherlands. The second group of countries with the slowest pace of transformation towards CE is formed by Cyprus, Czechia, Malta, Lithuania, Latvia, Hungary, Ireland, Slovakia, Romania, Estonia, Croatia, and Bulgaria. Interestingly, Claudio-Quiroga and Poza (2024) and Pintilie (2021) appreciate that there is a four-speed Europe in terms of the circular economy concept, highlighting the good results of the Netherlands, Germany, Italy, and Belgium.

The number of patents, which is the key explanatory variable, varies significantly between countries. The average value ranged from 0.66 in 2010 to 1.15 in 2014, whereas the standard deviation ranged from 0.75 in 2011 to 2.23 in 2014. The coefficient of variation for the entire period was 153%, indicating very large differences. The countries with the lowest average value of the indicator include Bulgaria (0.054), Croatia (0.070), and Greece (0.093). By contrast, the group of countries with the highest average value of the indicator consists of Luxembourg (6.404), Finland (3.039), and the Netherlands (1.453). In the case of countries like Bulgaria and Croatia, their low propensity to patent may result from the fact that these countries have significantly less R&D personnel and researchers in the share of total employment as well as governments environmental and energy R&D appropriations and outlays compared to such countries as Luxemburg, Finland, and the Netherlands. Fura (2020) stresses the leading role of Luxembourg in patenting the field of recycling and secondary raw materials. From an international perspective, Europe and the US are the leaders in innovation in plastic recycling and alternative plastic technologies. Europe and the US each accounted for 30% of patenting activities worldwide in these sectors between 2010 and 2019 (European Patent Office, 2021b). Within Europe, Germany has the largest absolute number of international patent families (IPFs). However, this situation reflects the size of the German economy rather than a real specialization in plastic recycling technologies. Among smaller European countries, the Netherlands has a strong technological specialization in plastic recycling, which is reflected in Dutch companies' prominent positions in the recycling industry (Hanemaaijer & Kishna, 2023).

Analysis of the panel structure of the data shows that for each variable, the between-group variation is much larger than the within-group variance. Therefore, we use a generalized estimating equation to estimate the parameters of a generalized linear model with a possible correlation between observations at different time points.

As previously mentioned, we apply GEE to estimate the population-averaged effects of eco-innovation activities on the use of circular materials in economic processes in European Union countries. We employ a working correlation matrix with an exchangeable within-group correlation structure (the same correlation between observations). To estimate the coefficient standard errors, we apply the Huber-White sandwich estimator. To address the issue of possible nonlinearities between circularity and its drivers, we include quadratic terms in our model. Adopting such an approach is anchored in the literature on the threshold effects of eco-innovation (Sun et al., 2022) and human capital (Kijek & Kijek, 2020), as well as the Environmental Kuznets Curve with the recycling hypothesis (Kasioumi & Stengos, 2020). We use backward elimination, starting with the model with all possible predictors (Table 1) and successively removing non-significant regressors. The results of the models with logit link function and exchangeable correlation structure are presented in Table 3.

Table 2. Descriptive statistics, correlations and panel decomposition of standard deviation of variables

Variable	Min	Max	Mean	Std. dev. overall	Between	Within
CIR	1.2	30	8.75	6.31	6.15	1.80
PAT	0	11.9	0.84	1.28	1.13	0.64
GDP	46	283	100.64	43.10	43.38	6.01
EDU	0.5	6.3	2.60	0.97	0.96	0.27
TET	4.33	11.75	7.48	1.75	1.71	0.50
OAD	17.2	35.8	27.32	4.07	3.74	1.75
Correlations	CIR	PAT	GDP	EDU	TET	OAD
CIR	1					
PAT	0.237*	1				
GDP	0.296*	0.740*	1			
EDU	–0.037	–0.156*	–0.187*	1		
TET	–0.235*	–0.319*	–0.465*	0.331*	1	
OAD	0.148*	–0.205*	–0.303*	0.202*	–0.025	1

The spatial distribution of the circular use of materials and the number of patents in 2010 and 2019 are presented in Figure 1.

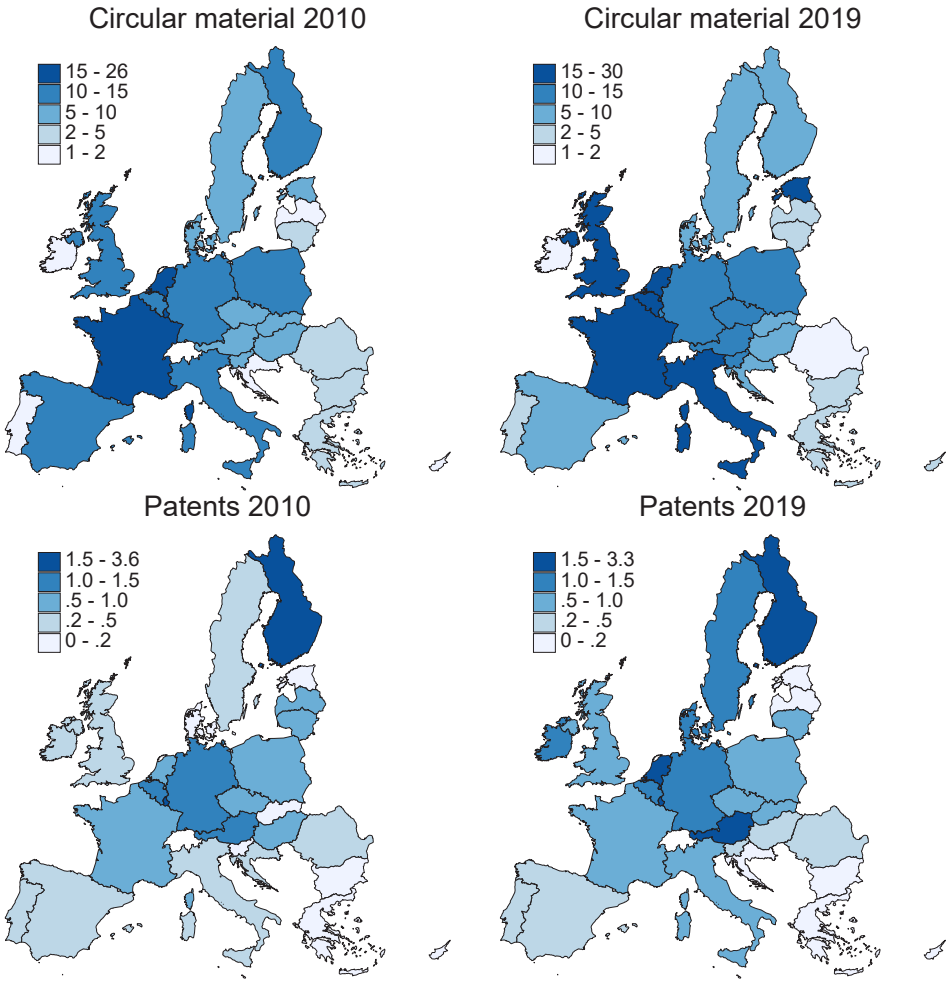

Figure 1. The spatial distribution of circular use of materials and number of patents

Table 3. Parameter estimates of GEE population-averaged model

CIR	(1)	(2)	(3)
PAT	0.021	-	−0.036
PAT^2	-	0.003***	0.005**
GDP	0.013***	0.015***	0.014***
GDP^2	−0.0001***	−0.0001***	−0.0001***
EDU	−0.447***	−0.444***	−0.433***
EDU^2	0.075**	0.075***	0.074***
cons	−2.602***	−2.721***	−2.659***
Wald chi2 (p-val)	24.01 (0.000)	102.12 (0.000)	273.48 (0.000)
QIC	132.769	132.648	132.945

Note: * p<0.10, ** p<0.05, *** p<0.01.

It can be observed that the model with patents only in quadratic form (Model 2) has the smallest QIC, and thus is chosen as the preferred model. The results show that patents have a positive and increasing impact on the circular use of materials. This finding confirms our hypothesis. Other studies also report the positive impact of eco-innovation on circularity. For example, Bao et al. (2023) study the nexus between environmental innovation and circularity in European economies. Their results show that EI-related patents have a negative impact on municipal waste per capita, which leads to an improvement in environmental quality. Contrary to our research, this study provides inconclusive findings on nonlinearity in the link between eco-innovation and circularity. The increasing returns to eco-innovation may arise from the cumulative knowledge stocks embedded in patents related to recycling and secondary raw materials. Notably, lower knowledge stocks of entrant technologies are a barrier to knowledge diffusion (Hötte, 2019). Barbieri et al. (2020) argue that green technologies protected by patents are different from non-green technologies. It is worth pointing out that green patents are more complex and provide greater knowledge spillovers, as manifested in their greater effect on subsequent technological inventions compared to non-green patents. Importantly, eco-innovation and CE targets are complementary. Since the publication of the European Union's Circular Economy Action Plan in 2015, most measures and almost all targets have increasingly focused on improving the recycling of different types of waste (Friant et al. 2021). According to Porter's hypothesis, strong regulations that limit environmental impacts force firms to engage in green innovation research and create markets for environmentally beneficial products and services (Porter & van der Linde, 1995).

Regarding the EKC with recycling, our results should be contrasted with the theoretical model developed by Pittel (2006), who shows that under certain initial conditions, preferences, and externalities arising in the recycling sector, the EKC (i.e., a hump-shaped path) for non-renewables may emerge during the transition to the long-run balanced growth path. This contradicts the argument proposed by George et al. (2015). In line with their model, environmental quality cannot be maintained or improved through economic growth. The former can be enhanced by increasing the environmental self-renewal rate or the recycling ratio. Similar to our study, Kasioumi and Thanasis (2020) examine the relationship between GDP per capita and recycling for 50 states in the United States and find an inverse U curve for the Middle Rich states.

Another factor with a nonlinear impact on the circular use of materials is human capital, measured by the EDU variable. We find that the positive effect of increasing the share of pupils and students with bachelor's degrees or equivalent levels in the total age population is triggered beyond a threshold, reflecting a critical mass of educated people. As such, we confirm the results of other studies that show a positive link between higher education levels and broader environmental consciousness of the CE (Neves & Marques, 2022), while shedding new light on a possible negative effect (Sánchez-Llorens et al., 2019). It is worth noting that our results neither corroborate nor contradict studies that point to either a positive association between age and willingness to recycle and/or waste generation (Nixon & Saphores, 2007) or a negative one (Chu et al., 2013). Finally, it emerges that total environmental tax revenues have insufficient statistical significance in explaining the circularity rate of the EU economies. This is hardly surprising, as Ha (2023) reveals the heterogeneous effects of an environmental tax on circularity and shows that circular material usage is affected the least when pollution and resource tax revenues increase.

CONCLUSION

The aim of this study is to analyze the link between eco-innovation and the circularity of EU economies. To do so, it investigates the role of patents related to recycling and secondary raw materials in the circularity rate. The empirical analysis applies annual panel data for 28 EU countries from 2010 to 2019. The three models are estimated using different specifications. The Huber-White sandwich estimator is used in all models. The main finding is that increasing gains in circularity are achieved through inventions related to recycling and secondary raw materials. This result provides a compelling rationale for prioritizing and incentivizing investments in promising technologies to achieve both environmental sustainability and economic prosperity in the long term. It should be noted that European universities and public research organizations are pioneering a range of technologies that foster reusability, recyclability, and waste recovery (EPO, 2021a). The major challenge face by many is bringing them to the market through innovative spinoffs or selling/licensing IPRs. KT Boost, a new knowledge transfer funding program for Irish universities and technological universities, is a good example of how to support knowledge transfer from universities and boost their innovative capacity and capability, whilst also supporting firms to access new knowledge and expertise, to drive innovation through collaboration, and to identify and license new technologies and IPRs (Government of Ireland 2023).

Additionally, we reveal that the relationship between the circular use of materials and GDP per capita is characterized by an inverse U curve. This means that the circularity ratio increases as the GDP increases until it reaches its highest point and then starts to fall. This may be due to several reasons. Most importantly, as GDP increases and countries grow richer, firms may invest more in circular materials to reduce environmentally harmful waste. However, as these activities become more expensive, their efficiency decreases. Therefore, new and more effective recycling methods must be developed and commercialized to overcome this problem. With respect to human capital, a critical mass of well-educated people is needed to provide and promote an effective transition to CE. In this situation, policymakers should increase the attractiveness of circular materials to consumers, particularly those with the least education.

This study has several limitations. These are mainly concerned with the sample size and ways to measure eco-innovation and its determinants. It should also be noted that due to the existing information gap (lack of some data), it was not possible to carry out regression analyses for a balanced panel of EU countries. Furthermore, because our analyses involve data for the EU countries only, for future research, some possible extensions could include data for selected OECD countries to increase confidence in the results we show in this paper. Additionally, future studies could apply different proxies for eco-innovation related to CE, such as green R&D and a broader set of other CE drivers, including both regulations and incentives.

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The authors declare no conflict of interest.

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Unitary patent system and innovation dynamics in the European Union: The role of economic resources and R&D investments

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Abstract

PURPOSE: *The EU supports competitiveness and sustainability via innovations by the patent protection of inventions. On 1st June 2023, the EU launched the Unitary Patent System (UPS) with the Unitary Patent as a universal innovation protection tool. The data regarding its first 20 months of operations offers indices about innovation and patenting trends.* **METHODOLOGY:** *The contextual exploration of the UPS was projected into four aims addressing the absolute and relative numbers of Unitary Patents (A1) and the relationship between Unitary Patents and GDP per capita (A2) and GERD (A3) and comparatively juxtaposing them (A4). This deeper contextual understanding of Unitary Patenting dynamic entails EU member states and their top four competitors (China, Japan, South Korea, USA). The data regarding the GDP, GDP per capita, GERD, number of Unitary Patents in total and per millions of inhabitants was collected and visualized via tables and charts, and submitted to a critical comparison.* **FINDINGS:** *The first 20 months of the UPS operations suggests that the Unitary Patent is a viable, but not the most popular, patenting option, and that there is a positive impact on the GDP per capita and GERD for the majority of the EU member states and that there are differences between EU member states in their efficiency to generate Unitary Patents.* **IMPLICATIONS:** *The performed study confirms the parallel co-existence of various patenting strategies and the importance of investments in patented inventions. However, the size of GDP per capita followed by GERD is a mere pre-requirement that leads to diversified efficiency (even among similar jurisdictions with at least an average GDP per capita and GERD. Arguably, the UPS magnifies the differences, and the six original European integration jurisdictions are not the best UPS players. There are indices about positive trends for Northern EU member states and negative trends for Southern EU member states.* **ORIGINALITY AND VALUE:** *This is a pioneering contribution regarding a newly launched system showing that, despite the same regime, EU member states differ dramatically in their approach to patenting and that the level of GDP per capita and GERD are just the starting points.*

Keywords: *Unitary Patent System, EU member states, GDP, gross domestic expenditure on research and development (GERD), GERD per GDP (GERD Index), innovation, sustainability, economic resources, patent protection*

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INTRODUCTION

The European history of a patent protection regime goes back to Renaissance Italy and Tudor England (MacGregor Pelikánová & Beneš, 2023) and reflects the belief about the significance and positive effect of innovations on the economy and society (Terzić, 2017), in particular for sustainable economic growth (Prędkiewicz & Prędkiewicz, 2014). A set of justifications for granting patents as temporary and territorial absolute rights (monopoly) has co-existed for centuries, and perhaps the most well-known is based on Bentham's consequentialism. An important conceptualization occurred nearly one hundred years ago when Joseph Alois Schumpeter theoretically analyzed the need to provide incentives for ideas (inventions), to protect them via a temporary monopoly (patents) and to facilitate their speedy transposition and implementation (innovations) (Schumpeter, 1934). Further, already by then, it was well established that human ideas about resolving various problems and doing better things (effective) in a better way (efficient) could be achieved by various human mind outcomes deserving different types of protection – a creative work by copyright, a solution of a technical problem by a patent, etc. (MacGregor Pelikánová, 2019). To the most prevalent and expensive are inventions as solutions to technical problems, which are protected by a national or set of national patents. To put it differently, already about 250 years ago, James Watt knew that his R&D activities desperately needed financing, and their outcome must avoid waste and be properly transposed (by innovations) and protected (by patents and trade secrets) (Crass et al., 2019).

Now, more than ever before, the human mind activities and investments are linked to innovation and sustainability (Lashitew et al., 2024) and require smart and willing minds, incentives, and investment (Koellinger, 2008). The circle is getting closed, and the question is not whether but instead how. Thus, pursuant to the prevailing tenor in the EU, innovativeness depends upon the financing of R&D (Nunes et al., 2012) and is to be measured based on the number of patents granted (Prędkiewicz & Prędkiewicz, 2014). The EU wants to boost its competitiveness and sustainability by supporting the financing of R&D and by facilitating the patenting regime (MacGregor Pelikánová & Beneš, 2023). Ultimately, this should contribute to the building of a common industrial policy in the EU encompassing jurisdictions with diverse socioeconomic interests (Plomer, 2015) and to the proper use of business property and investments (Paksiova & Kubascikova, 2015).

Consequently, on 1st June 2023, the EU launched the unified single patent protection via the Unitary Patent (UP) with the Unitary Patent System (UPS) which should be a universal tool to be employed by EU businesses. Therefore, there is a unique and basically first-time-in-the-world opportunity to file one patent application and get not just one national patent or a bundle of national patents, but a super patent protecting the invention in the majority of EU member states. The data regarding the one year of granting of Unitary Patents offers a set of highly interesting indices and helps to fill in the current vacuum about the universality and effect of Unitary patents, in particular, whether this instrument meets the high expectations of the EU, especially the European Commission.

This implies that new research interest in the contextual exploration of the newly launched UPS projected into four aims addressing the absolute and relative numbers of Unitary Patents (A1) and the relationship between Unitary Patents and GDP per capita (A2) and GERD (A3) and comparatively juxtaposing them to see emerging clusters, pairs and trends (A4). Therefore, a theoretical background, framework setting and literature review are to be presented. Then, based on them, proper data is to be collected, visualized, and discussed for all EU member states and their top four competitors (China, Japan, South Korea, USA) regarding their absolute and relative number of Unitary Patents, GDP per capita, the gross domestic expenditure on R&D (GERD) as the percentage share of GDP (GERD Index), and to be visualized by tables and charts and submitted to a critical comparative juxtaposition refreshed by glossing. This should lead to the contextual presentation and juxtaposition of results regarding the use of the Unitary Patent, emerging trends, the impact of GDP per capita, GERD and GERD Index and differences between EU member states and their four top competitors regarding their interest and perhaps even efficiency in generating Unitary Patents as precursors of innovations.

THEORETICAL BACKGROUND, FRAMEWORK SETTING AND LITERATURE REVIEW

The concept of sustainable development has millennial continental law roots and is based on a "right and just" generation, distribution, and use of resources (MacGregor Pelikánová et al., 2021). It is marked by a systematic transformation and a multidisciplinary connection of ideas, theories and methods while demanding the engagement of both individual and collective responsibility (Fitzpatrick, 2023) within and between intersecting and mutually intra-related spheres (Dodman et al., 2020). Among the moving forces were the state establishment changes and innovation, in particular since the beginning of the First Industrial Revolution (1750-1760). In 1776, the Scottish economist and philosopher Adam Smith published

The Wealth of Nations, focused on the specialization and division of labor and the increase in productivity and the Scottish inventor James Watt improved the modern steam engine. Interestingly, as much as Adam Smith wanted to avoid the waste of labor, equally as much did James Watt want to avoid a waste of energy by repeatedly cooling and reheating the cylinder, see his design advancement by the separate condenser. It can be even suggested that the modern three pillars concept of sustainability (Purvis et al., 2019) is a demonstration of the avoidance of waste as perceived by these two Scottish thinkers. Finally, it is important to remember that James Watt struggled to obtain financing for his research and development (R&D) activities, while Adam Smith did his best to help. Once Watt managed to obtain the financing via a business partnership, he managed to come up with a set of great inventions which he ultimately managed to put to work, i.e. turn them into innovations, while protecting some of his inventions via trade secrets and others via patents yet infringements happened, law and arbitration proceedings followed and ultimately ended with law settlements. How prodigal.

The development, preferably sustainable development, should be an inherent part and consideration of business strategy (Petera et al., 2021) and match up with the Porter based 3+ core paths to a competitive advantage (Moon et al., 2014). The combined effect of the, so far, four Industrial Revolutions, demonstrates the inclination of humans to transform the environment permanently and irreversibly (Barbiero, 2021), the importance of creating and sharing knowledge (Dodman et al., 2020), see Society 4.0 (Turečková et al., 2023a) and their drive to resolve problems while using technology (MacGregor Pelikánová & Beneš, 2023). Such endeavors often lead to the exhaustion of diminishing resources in a selfish manner (Barbiero, 2021) and can have permanent, irreversibly and highly negative social and environmental consequences, of which probably the worst is climate change (Jones et al., 2023: 4). Manifestly, currently, we are facing the imbalances and inequalities of the resources and their use (Dodman et al., 2020), as well as values discrepancies (MacGregor Pelikánová & Sani, 2023). It is justly suggested that the current concept of sustainability desperately needs humans to overcome their selfishness and drive for immediate and often reckless gratification (D'Adamo, et al. 2024) and employ their intellectual potential to generate intellectual property assets and solutions to boost the effective, efficient and, most importantly, responsible competitiveness (MacGregor Pelikánová, 2019). This all should lead to the satisfaction of the ongoing need for development, ideally sustainable development, taking advantage of innovations and technologies.

The desire for the development of the society leading to growth is deeply embedded in our civilization (Panta, 2019) and has led to a set of foundational and conceptual ideas projected in various theories, starting with mercantilism, physiocracy and classical theories and, so far, ending with neoclassical and endogenous theories (Saikia et al., 2023). Pursuant to the classical growth theory, the positive effect on the growth has the decline of the population and the increase of resources, i.e. in the case of limited resources the growth can be achieved by the population drop and the significance of technological advancement and innovations is underplayed, if not completely ignored. Pursuant to the Schumpeter growth theory, this is the other way around, i.e. innovations are critically important (Schumpeter, 1934) and Keynesian theories of the government intervention are needed to stabilize the economy and stimulate R&D and innovations. Pursuant to the neoclassical growth theory, the growth rests on three mutually related pillars – economic forces: labor, capital and technology, in particular there is advanced the idea that the (external) innovations increase efficiency. In contrast, pursuant to the endogenous growth theory, the pivotal role is to be played by internal factors and forces, i.e. the growth is not imported from outside sources and technologies, but rather is generated by the internal drive for R&D and resulting technological progress. Consequently, basically all growth theories for the last century, including both the neoclassical growth theory and endogenous theory, link the desired growth to innovations and are aware about the need to invest, to get inventions and to turn them into innovations (Saikia et al., 2023). However, it must be admitted that capital and labor are easily defined drivers of economic growth (Solow, 1956), while, in contrast, technical and technological progress appears ephemeral and not easily grasped (Blind et al., 2021). Further, it must be admitted that the relationship between investment, R&D, inventions, their protection by patents and implementation via innovations, and economic and other growths is neither clearly linear nor exponential and that the resulting models and curves differ across industries and jurisdictions (Das, 2020). Currently, pursuant to the growing tenor, it is about both effectiveness and efficiency regarding inventing, patenting and innovating. Without investing in R&D and conducting R&D, innovations can hardly emerge leading to growth and general wellfare improvement and even the best planned and spent investing in R&D is futile if no proper researchers are available (Blind et al., 2022). At the same time, excessive and misplaced R&D spending generates social costs and is contra-productive (Das, 2020), excessive and misplaced patenting stifles innovations and suffocates the progress and development (Jurek, 2024) and a wrong consideration or engagement of labor capital buries any growth and progress prospects (Blind et al., 2024).

The EU shares the vision that resources are needed for inventions and even more for innovations and shapes its policies and law accordingly in the hope of promoting growth (Billon et al., 2017), which should ideally lead to sustainable development (Balcerzak et al., 2023). To put it differently, the EU knows that sustainable development and competitiveness cannot be achieved in our highly competitive global society without financing for inventions and innovations (Dima et al., 2018), and without a shift from tangible to intangible resources (MacGregor Pelikánová, 2019) and without providing copyright protection for original works (Polanski, 2015) and industrial property protection via patents for inventions (Potužáková & Öhm, 2018). Both the sustainability and competitiveness need creative solutions for pre-existing problems (inventions) to be implemented (innovations) while receiving the very needed temporary monopolistic protection (patents) (MacGregor Pelikánová & Beneš, 2023). Further, the EU acknowledges that financial support for R&D is both necessary and limited (Blind et al., 2017) and that R&D has effects on profitability from various perspectives (Ciftci & Cready. 2011). Similarly, the EU recognizes that, although innovative assets are profitable (Czarnitzki & Kraft, 2010), inventions and innovations leading to them are typically the result of an unpredictable and financially demanding research and transposition process generating valuable intellectual property assets, i.e., knowledge efficiency (Polcyn, 2018) and that costs and risks are their integral and inevitable parts (MacGregor Pelikánová, 2019). Further, both EU policies and the academic tenor argue for the positive impact of patent protection for inventions and innovations and the synergy effect with respect to competitiveness and sustainability (MacGregor Pelikánová & Beneš, 2023). However, EU member states and Europeans themselves have very different views regarding the ideal regime, exact amount of financing for R&D (Hammadou et al., 2014), related super-deductions (Jancickova & Paksiova, 2023), the project management and realization (Szopik-Depczyńska et al., 2024), etc., and these differences are often cluster-linked (Prokop et al., 2024).

The EU keeps closely following the United Nations' (UN) pro-sustainability approach and shapes its policies and law accordingly (MacGregor Pelikánová et al., 2024). This well- established EU trend continues through our uncertain and turbulent times (Van Tulder & Van Mil, 2023: 1), crises such as the Covid-19 pandemic (Hála et al., 2024) or War in Ukraine (Malý et al., 2023) and generally events inducing scepticism (Szántó & Dudás, 2022) and challenging trust, the sustainability readiness and values orientation (Hála et al., 2022). Indeed, crises arguably magnify differences, accelerate pre-existing trends and even, pursuant to Einstein, should bring progress due to inventiveness because they generate unique opportunities (D'Adamo & Lupi, 2021). Therefore, rain or shine, instruments induced by the UN, such as the Brundtland Report Our Common Future from 1987 or Agenda 2030 from 2015 or the Paris Agreement from 2015, have become building blocks of EU policies and law along with the integration, competitiveness, agriculture and rural development concerns. Indeed, already in 2010, the EU formulated its decade-long strategy, Europe 2020, based on three mutually reinforced priorities (smart growth, sustainable growth and inclusive growth), centered around five objectives and seven flagship initiatives. Pursuant to Europe 2020, at least 3% of the EU's GDP was to be invested in R&D by 2020 to boost innovations along with the competitiveness and sustainability (MacGregor Pelikánová & MacGregor, 2020). Although many policy and law initiatives were taken and even completed, including in the arena of the protection of intellectual property, many objectives of the Europe 2020 were not met, including the hallmark of 3% investment (MacGregor Pelikánová, 2019). However, the European Commission of Ursula von der Leyen decided to move even further, with its Political Guidelines for 2019-2024 Keeping our promise to Europe with the famous six priorities, of which the very first is the European Green Deal (EGD), see COM(2019) 640 final. The EGD determination to transform the EU's economy and society while putting them on a more sustainable path moves the EU's meta-discourse from a negligence of environmental sustainability (2000 Lisbon Strategy) over to the idea that sustainability is linked to competitiveness and innovations and so can support a 'jobs and growth' agenda to a systemic center-stage incorporation (Schunz, 2022). Although the new European Commission of Ursula von der Leyen makes, regarding 2024-2029, some pragmatic and pro-competitiveness modifications, especially due to national inherent particularities (Jarzemskis & Jarzemskiene, 2022), the EGD is not to be abandoned, instead circularity and renewability are to be supported (Balcerzak et al., 2024) and a larger pool of subjects should be actively involved, see e.g. the new legislation to involve customers in the greening of the economy (MacGregor Pelikánová, 2024).

However, this enthusiasm and drive of the EU, in particular the European Commission, is not fully shared by all EU member states and Europeans (Szántó, 2019), which are open to declare their commitment to support innovations and sustainability as an integral component of their competitiveness (Šlapáková Losová & Dvouletý, 2024), but much less open to share the unified pro-sustainability and pro-competitiveness attitude advanced by the EU (D'Adamo et al., 2022) and to recast their innovations and patenting setting (Scellato, 2007). This is entirely opposed to the European Commission and its reports, such JRC Technical Reports about green and digital inventions, which link the sustainable development, SDGs

and patenting (Bello et al., 2023). The persistent lack of readiness to spend a larger part of GDP on R&D as demonstrated, sadly, by the majority of the EU member states, along with their reluctance to accept a unified intellectual property protection system, undermines ongoing EU endeavors and ultimately are one of the many reasons why EU inventiveness and innovations are not fully explored and cannot massively boost competitiveness and sustainability. Perhaps the EU is overly enthusiastic and more future oriented, while EU member states are rather pragmatic and focused on the present, see the current saga about EGD with circular economy projects. EU member states correctly point out that many inventions have a problematic usefulness and do not support sustainability and competitiveness, as a matter of fact, they can be contra-productive, see e.g., inventions and innovations regarding electric vehicles (D'Adamo et al., 2022). Pursuant to the national tenor, it is not about any inventions and any patents at any price, but about an effective, efficient, legitimate and pro-sustainability and pro-competitive system which is lean, respects national particularities as appropriate and works. In contrast, pursuant to the supra-national regional tenor of the EU, the integration needs the unification, or at least the harmonization, in the intellectual property arena, and this can be observed in the rather smooth unification regarding EU trademarks and the harmonization of national trademarks as well as on the turbulent and extremely challenging and not yet completed Odyssean journey of patent protection unification in the EU (Kaesling, 2013).

Already before the Europe 2020, the EU engaged with the idea of a single community patent system based on typical regulations. In contrast to the EU trademark legislative package, which was initiated in 2008 and led to the harmonizing Directive (EU) 2015/2436 and unifying Regulation (EU) 2015/2424, the original plan about the same for the patent regime failed, due to massive objections to the language mechanism (English, French and German only) voiced by certain EU member states in 2010, and to the proposed Patent Court (and its incompatibility with the EU law) voiced by the CJ EU in 2011 (MacGregor Pelikánová & Beneš, 2023). Therefore, in 2015, i.e,. around the same time as when the EU trademark reform was completed, a new attempt regarding the unification of the European patent system was launched and slowly progressing. This time, there was envisaged a three-pillar structure of the European Unitary Patent System (UPS) consisting of:

- EU Regulation No 1257/2012, which creates a "European patent with unitary effect", commonly referred to as "Unitary Patent";
- EU Regulation No 1260/2012, which lays down the translation arrangements for Unitary Patents;
- The enhanced co-operation Agreement on a Unified Patent Court (UPC Agreement) from 2013 was allowed by the decision of the Council of Ministers of the EU 2011/67/EU.

One decade later, on 1st June 2023, the entire UPS was launched and a growing number of applicants which obtained a European Patent also opt for the Unitary Patent, i.e., in Summer, 2023 less than 20% opted to do so, while in Summer, 2024 more than 30% opted to do so, seethe ongoing statistical information by the EPO dashboard. A growing interest is noticeable especially by subjects from the EU.

The Unitary Patent is based on a European Patent, which is not a patent per se providing an absolute monopoly in Europe, instead the European Patent is a title generated by a centralized proceedings which allows one to obtain a bundle (set) of national patents. Namely, the European Patent is a document granted by the European Patent Organization (EPO), located in Munich, under the rules and procedures of the European Patent Convention (EPC), which was signed in 1973 in Munich, and is linked to the Council of Europe and has 39 member states (27 EU member states and 12 other countries). Similarly, the Patent Cooperation Treaty (PCT), which was signed in 1970 in Washington, is linked to the Paris Convention signed in 1883, is administrated by the World Intellectual Property Organization (WIPO) in Geneva, has 157 member states and can lead to a bundle of national patents in these jurisdictions. Plainly, the EPC and the EPO are competing systems with the PCT; they both lead to a bundle of mutually independent national patents that need to be maintained and defended independently and separately.

In this context, it is relevant to observe the evolution of the dynamics of patenting trends by the top four EU competitors. Namely, since 1960, there has been a growth in international patenting intensity, entailing both patenting effectiveness and efficiency, in China, Japan, and South Korea (O'Keeffe, 2005). As a matter of fact, the panel data indicates the positive correlation of GDP and the number of granted patents in Japan and South Korea (Sinha, 2008) and an almost unprecedented surge regarding international patenting by China since 2010 (Jiang et al., 2019). The Bank of Japan observes that the efficiency of R&D investment in Japan has recently declined and that the ultimate loss of momentum for inventing, innovating and patenting is due not only to the amount of investment and the appropriateness of its use, but as well to the population decrease and general decline in the number of researchers and intellectual property experts, along with their lack of diversity (Oh & Takashi, 2020). Perhaps this is the secret of the innovation and growth success of the

USA as well as Scandinavian countries, because they not only have a fine GDP/capita and also a more than good readiness to spend on R&D, but, in addition, they excel with respect to labor research productivity and diversity (Blind et al., 2021). Throwing money in the right direction where nobody is ready to invent is futile.

The Unitary Patent is an alternative to avoid the fragmentation, i.e., once the European Patent is granted by the EPO, the successful applicant has a choice to either conventionally continue based on the EPC and get selected national patents and keep taking care of each of them, or to take advantage of the new UPS and instead turn his European Patent into the Unitary Patent, which covers a number of jurisdictions in the EU. In such a situation, a one-stop-shop only has one renewal fee to be paid annually, only one proceeding is to be done, etc. One for all and all for one, i.e., as well an attack in one jurisdiction means a potential collapse of the entire patent protection. The UPS with the Unitary Patent is an option offered under the auspices of the EPC-EPO since 1st June 2023. The EU, in particular the European Commission, was and remains convinced that the UPS with the Unitary Patent will reduce the complexity, formalities and costs and ultimately help inventors and innovators in their pro-sustainability, pro-digitalization and pro-competitiveness endeavors (MacGregor Pelikánová & Beneš, 2023), and this despite UPS "disjointed legal mosaic" features (Plomer, 2015). In sum, the UPS and Unitary Patent should be an intersection flagship initiative boosting most, if not all, of the Six priorities.

Well, both the UPS and UPS membership have developed in a rather turbulent manner not allowing to process with an automatic assessment. The statistics calculations about the use of the UPS and granted Unitary Patents are impaired by the brief existence (less than two years), the existence of other options leading to similar results, and membership fluctuations due in particular to the enhanced co-operation leading to the UPC Agreement. Namely the UPS first and second pillars are Regulations back from 2012, while its third pillar is the UPC Agreement from 2013, which was to be signed by EU member states participating in the enhanced co-operation. Originally, there were 25 involved EU member states, including UK and partially as well Bulgaria and Italy, but except Croatia, Poland, Spain. At the moment of the launching of the UPS, there were 24 (UK left and still Croatia, Poland and Spain out) of which 17 ratified it, while the ratification by Romania in May 2024 took effect in September 2024 bringing the number of the full UPS members to 18. Consequently, in February 2025, the status quo regarding the UPS is that the UPC Agreement is not yet signed and thus cannot be ratified by three EU member states (Croatia, Poland, Spain) and six have signed it but have not (yet) ratified (Cyprus, Czechia, Greece, Hungary, Ireland, Slovakia) it. This means that any Unitary Patent is a one-stop-shop title to absolute monopoly protection in 18 jurisdictions, i.e., instead of 18 national patents is one unitary. Specifically, Unitary Patents registered from 1 September 2024 onwards cover the territory of the following 18 EU member states (second generation of Unitary Patents): Austria, Belgium, Bulgaria, Denmark, Estonia, Finland, France, Germany, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Portugal, Romania, Slovenia, Sweden. This implies the interest regarding the contextual exploration of the, so far, only 20 months operating UPS as projected into four aims addressing the absolute and relative numbers of Unitary Patents (A1) and the relationship between Unitary Patents and GDP per capita (A2) and GERD (A3) and comparatively juxtaposing them to see emerging clusters, pairs and trends (A4) regarding these 18 EU member states, the remaining 9 EU member states and the EU top four competitors (China, Japan, South Korea, USA).

DATA AND METHODS

Factors for obtaining patents, in particular Unitary Patents, are heterogeneous, and the information sources about them are diverse. How much is available to be spent (being rich and having the resources to be spent), how much and how is it spent (being committed to spending), on what and whom is it spent (having capable and smart carriers of innovations and patenting)? These are some of the questions raised regarding factors leading to patented inventions. Naturally, the principal source of such data on factors is the Eurostat, which is the statistical office of the EU, which has as its mission providing high-quality statistics and data on Europe. The Eurostat keeps and updates numerous datasets, indicators, etc., and makes them freely available to the public. Thus, the annual data regarding GDP, GDP per capita, population and GERD for each EU member is freely available from both Eurostat and the World Bank. The European Patent Office (EPO) keeps the Unitary Patent Dashboard with the data about the number of granted Unitary Patents (per millions of inhabitants, granted during the last 20 months as well as subsequences of this time period July 26, 2024). The time progression of the patenting process implies the appropriateness to work with GERD and GDP per capita at least from 2019 to 2022 in the context of Unitary Patents from 2023-2025.

The inherent dynamics of investment and patenting and the openness of the Eurostat, World Bank, and EPO dashboard allow for the collection of relevant data about the economic health and strength of each EU member state

as condensed into GDP and GDP per capita in a given year, their commitment and readiness to spend a part of their GDP on R&D as expressed by the Gross domestic expenditure on research and development index (GERD Index), and ultimately the number of unitary patents obtained (Potužáková & Öhm, 2018). Such data has the potential to be both statically visualized as well as critical juxtaposed. Consequently, the data creates a foundation for future (based on more than 20 months long experience with Unitary Patents) objective, measurable, and statistically robust study based on an appropriate research design (Yin, 2008). To put it differently, this study is a first (and very necessary) step towards a multispectral and encompassing content analysis (Krippendorf, 2003) with descriptive, quantitative and qualitative features (Kuckartz, 2014) and able to produce results meeting standard validity, reliability and robustness expectations (Vourvachis & Woodward, 2015). The research aims to target obtained Unitary Patents while considering GDP per capita and GERD of jurisdictions of patent holders spending years and years on inventions and their patenting.

The research design faces three challenges (types of intellectual property protection available, time of data, and the size of EU member states), which could undermine the case study's coherence and need to be considered as potential limitations (Yin, 2008).

Firstly, sustainability can be achieved without innovations, and innovations can be protected by trade secrets or other non-patent instruments (Crass et al., 2019). However, considering prior studies as well as EU and national policies and laws, along with various intellectual property academic streams, it is obvious that at least a significant percentage of innovations should be and are protected by patents, that a growing number of Europeans prefer Unitary Patents over old-fashioned European patents leading to bundles of national patents, and that sustainability needs smart, effective and efficient solutions for pre-existing problems and so is inherently dependent on inventions which should lead to patented innovations.

Secondly, not only is investing one of the many factors that are leading to innovations and patents, but in addition the patenting process can have a variable length and success rate (generally very low). Prior studies suggest a time lag between R&D spending and generating profits from patents to the extent of four to six years (Ravenscraft & Scherer, 1982), but admit an earlier start of realizing returns (Prędkiewicz & Prędkiewicz, 2014) and point to various stages of the patenting process (MacGregor Pelikánová, 2019). To offset these timing issues, the data was collected in a chronologically dynamic manner – GERD Index for 2022, GDP and the number of inhabitants in 2023 and Unitary patents in 2023-2025. The philosophy behind this reflects the interest in the freshest data and, at the same time, the fact that the commitment to spend on R&D must be well established and seldom leads to results within two years (GERD Index), while recent economic health and strength should be considered (GDP) and all Unitary Patents should be taken into account, i.e. from 1st June 2023 to 31st January 2025 (the newest data available as of the day of collecting the data for this study).

Thirdly, the EU member states have different sizes and, for comparison purposes, the GDP/capita is typically used. Similarly, this study addresses the granted Unitary Patents, i.e., the fraction based on the population. However, due to the nature of the nominal level differentiation (the population is counted in millions while Unitary Patents in units), instead of Unitary Patents per capita, there is used the proportion of Unitary Patents per one million inhabitants.

The research design addresses the interest regarding the contextual exploration of the so far only 20 months operating UPS as projected into four aims addressing the absolute and relative numbers of Unitary Patents, in particular, the share of European patent holders opting for Unitary Patents and the number of Unitary Patents per one million inhabitants from the (A1) and the relationship between Unitary Patents and GDP per capita (A2) and GERD (A3) and comparatively juxtaposing them to see emerging clusters, pairs and trends (A4). This should be done in order to achieve a deeper contextual understanding of Unitary Patenting dynamics for EU member states and their top four competitors (China, Japan, South Korea, USA).

This implies the need to proceed in a four-step consecutive manner, to use visualization by tables and charts, and to develop a critical comparative juxtaposition refreshed by glossing (Hyland, 2007) and Socratic questioning (Areeda, 1996) in order to achieve a deeper contextual understanding. Since the Unitary Patens are only available for 20 months and the impact of GDP per capita and GERD on the current number of Unitary Patents may occur with a time lag, this entire study is rather a pioneering pilot project creating the foundation for future longitudinal studies which should overcome its inherent and so far inevitable limitations and consider variables, regressions and models.

RESULTS AND DISCUSSION

The contextual exploration of the so far only 20 months operating UPS is logically to be performed in four consecutive steps reflecting its four aims addressing the absolute and relative numbers of Unitary Patents (A1) and the relationship

between Unitary Patents and GDP per capita (A2) and GERD (A3) and comparatively juxtaposing them to see emerging clusters, pairs and trends (A4) of Unitary Patenting dynamics by EU member states and their top four competitors (China, Japan, South Korea, USA).

Unitary Patents – 20 months around

Pursuant to general expectations as well as public speeches of EU officials, the UPS should become promptly an attractive option to holders of European Patents who should prefer to go for the Unitary Patent instead of the bundle of national patents. This (allegedly) cheaper and easier option should be more effective (having a better protection) and efficient (easier enforceable), in particular for businesses from EU member states. Following this logic, the number of requests to turn European Patents into Unitary Patents should be climbing, especially considering holders from the EU, and this trend should be visible even from the period of the first 20 months. Plainly, the so far available data from EPO dashboard about the Unitary Patents, i.e. Unitary Patents requested and received between 1st June 2023 and 31 December 2025, should offer hints in this direction. Naturally, this period is rather short, we deal with inherent patenting time delays (see above) and we work with annual data not covering the entire year (June – December 2023, January – December 2024, January 2025), but still it is highly illuminating, see Table 1.

Table 1. Unitary patents - overview

	1 Jun – 31 Dec 2023	1 Jan – 31 Dec 2024	1 Jan – 31 Jan 2025	All (1 Jun 2023 – 31 Dec 2025)
Received requested for Unitary Patents	17259	28124	3078	48461
Obtained (granted/registered) Unitary Patents	17072	28023	2732	47827
Uptake rate EU	26.3%	37.3%	37.2%	32%
Uptake rate Global	17.5%	25.6%	25.9%	21.8%

Source: Prepared by the Authors based on EPO dashboard (Unitary Patents). Retrieved from https://www.epo.org/en/about-us/statistics/statistics-centre#/unitary-patent

The message generated by Table 1 is clear, Unitary Patents represent an interesting option, but definitely this is neither the massively preferred one nor progressively getting more popular. As a matter of fact, European businesses are more inclined to go for it than businesses outside the EU. However, still the majority of European businesses prefers to turn their European patents into the old fashioned bundle of national patents in several selected EU member states rather than the Unitary Patent. In addition, there are no indices about a drastic change, instead it looks like the, so far, peak was reached in summer 2024. Consequently, it was taken advantage of EPO dashboard data from 1st June 2024, first year anniversary of the UPS, to look deeper in the national distribution, i.e. from which EU member states were businesses obtaining Unitary Patents. Considering the dramatic diffirences in the population of EU member states and the need to achieve a contextual comparison, the number of Unitary Patents per one million inhabitants was considered. This led to the preparation of the graph showing how many Unitary Patents were obtained per million inhabitants from EU member states, see Figure 1.

The message provided by Figure 1 is very clear again. Namely, businesses from Denmark, Sweden and Finland are the most inclined to go for patenting and obtaining Unitary Patents while businesses from Romania, Croatia and Bulgaria are the least interested. Naturally, this message is rather a preliminary suggestion demanding a much deeper analysis. Nevertheless, as a fast snapshot shows, where in the EU is Unitary Patenting performed, where not and where some particularities demanding further explanation occur, see e.g. extremely good results for Luxembourg and unexpectedly good results for Malta. In any case, the overwhelming dominance of Unitary Patenting per million inhabitants in Scandinavia calls for further explanation, such as the impact of the GDP per capita or GERD.

GDP per capita and Unitary Patents – richness for patenting

As explained above, inventions and their patenting protection require both time and money. In particular, the time progression of the patenting process implies the appropriateness to work GDP per capita (in USD) during 2019-2023, if Unitary Patents are to be considered. In order to achieve an enhanced, revealing effect, the visualization of GDP per capita with the time evolution (2019 v 2023), is presented in Figure 2.

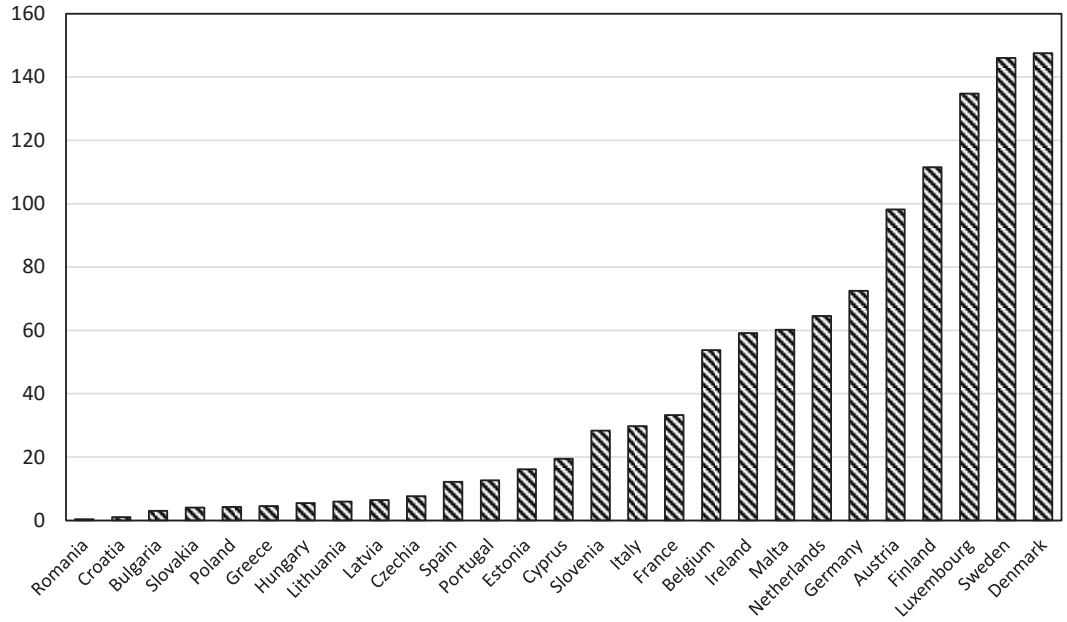

Figure 1. Number of Unitary Patents per millions of inhabitants in EU member states to 1st June 2024

Source: Statista, Eurostat (million inhabitants), EPO dashboard (Unitary Patents).

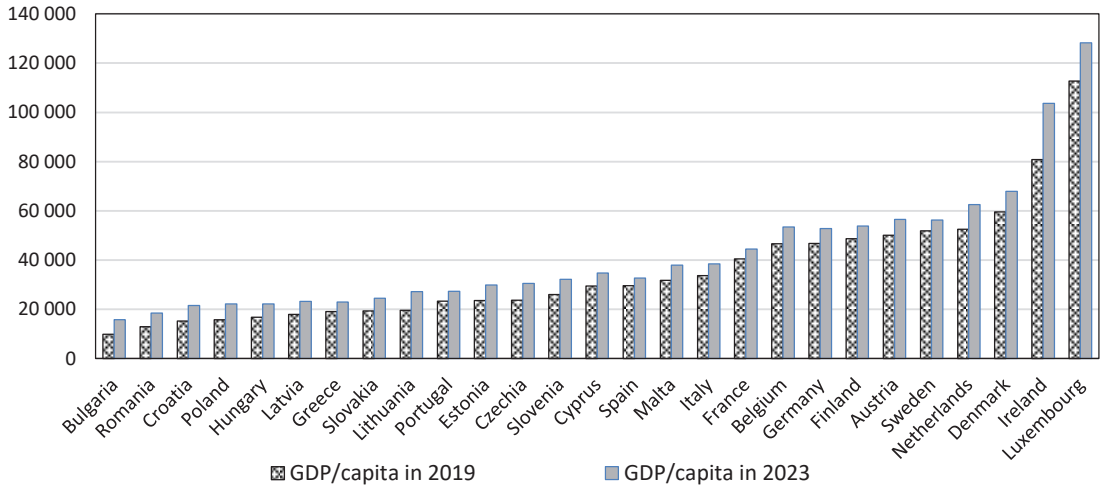

Figure 2. GDP per capita in USD in 2019 and 2023 (all EU member states)

Source: Statista, Eurostat, World Bank (GDP per capita), EPO dashboard (Unitary Patents).

Manifestly, no dramatic changes have occurred in GDP per capita in EU member states between 2019 and 2023, so there remain the same high differences in GDP per capita among EU member states. The GDP per capita of Luxembourg is 8x higher than that of the last place, Bulgaria. Generally, West and North EU member states reach a higher GDP per capita than South and East EU member states.

Considering the UPS and the full participation of 18 EU member states, it is relevant to mention that, within the half of the EU member states with a higher GDP per capita there is only one that is not fully participating in the UPS (Ireland), and that typically the 9 EU member states not fully participating in the UPS are states with the lowest GDP per capita (Croatia, Poland, Hungary, Greece and until recently Romania). This suggests that "richer" EU member states are more inclined to be in the UPS than "poorer" EU member states. A similar pattern exists regarding GERD, respectively GERD Index, in 2019 and 2022, see Figure 3.

Regarding GDP per capita and the number of Unitary Patents granted, it is highly interesting to observe four clusters – two clusters with a very high GDP per capita in 2023, see Table 2, and two clusters with a very low GDP per capita in 2023, see Table 3.

Table 2. Unitary Patents per millions of inhabitants by 1st June 2024 in EU member states with a high GDP per capita in 2023

EU member state	Country Code	GDP per capita in euros in 2023	Number of UP per millions of inhabitants by 1st June 2024
Austria	AUT	52 370	98.13
Belgium	BEL	49 720	53.74
Denmark	DNK	63 290	147.45
Finland	FIN	49 280	111.51
France	FRA	41 330	33.23
Germany	DEU	48 770	72.47
Sweden	SWE	51 000	146.02

Source: Statista, Eurostat, World Bank (GDP and GDP per capita in 2023), EPO dashboard (Unitary Patents by 1st June 2023).

Table 2 includes the EU member states with the highest GDP per capita while omitting Luxembourg and Ireland due to a strong external impact on their GDP and their copyright inclination. The Scandinavia trio (Denmark, Finland, Sweden) has a similar GDP per capita as the foundation EU trio (Belgium, France, Germany) but is roughly two times more efficient in getting Unitary Patents. The biggest, most obvious difference occurs between Belgium and Finland. These two member states have basically the same GDP per capita. Still, Finland is twice as efficient in getting UPs. However, the GDP of Belgium is more than two times larger than that of Finland; both states have basically the same absolute number of Unitary Patents (632 and 622). Even more worrisome is the situation of France, which has a comparable GDP per capita to Finland and Germany and is not only almost one-fourth as efficient as Finland, but even Germany is twice as efficient as France. To complete this overview, it is good to mention that Austria is the closest one to reach the level of the Scandinavian trio. This points to the recognition that although clichés and national and other stereotypes are typically misleading generalizing tools, they might still have elements of merit (Hřebíčková *et al.,* 2018), particularly in the arena of sustainability and innovations in the EU (Szántó, 2019). Well, it appears that free creativity, personal and organizational discipline, individual responsibility, and openness to co-operate are definitely important for patenting, and the EU member states with high GDP per capita (Turečková *et al.,* 2023b) differ in them significantly (Prokop *et al.,* 2024). Well, the situation for lower GDP per capita states reflects the same pattern, see Table 3.

Table 3. Unitary Patents per millions of inhabitants by 1st June 2024 in EU member states with a lower GDP per capita in2023

EU member state	Country Code	GDP per capita in euros in 2023	Number of UP per millions of inhabitants by 1st June 2024
Czechia	CZE	29 180	7.63
Estonia	EST	27 590	16.11
Greece	GRC	20 920	4.46
Hungary	HUN	20 480	5.42
Latvia	LVA	21 440	6.38
Lithuania	LTU	25 070	5.92
Poland	POL	19 920	4.17
Portugal	PRT	25 740	12.60
Slovakia	SVK	22 210	3.98

Source: Statista, Eurostat, World Bank (GDP and GDP per capita in 2023), EPO dashboard (Unitary Patents by 1st June 2024).

Table 3 includes EU member states with a lower (but not the lowest) GDP per capita, i.e., between EUR 19 920 EUR and EUR 29 180. Interestingly, Slovakia, Greece, and Poland have a similar GDP per capita and very low Unitary Patent performance. In contrast, the highest patenting performance is achieved by Estonia, Portugal, Czechia and Latvia, while Czechia has a significantly higher GDP per capita than Latvia. It might be speculated that the obvious handicap of a smaller GDP and GDP per capita is addressed very well by Estonia and Latvia and very poorly by Slovakia and, to a certain extent as well, Poland and Greece. This might point to historical, cultural and production orientation backgrounds, such as that EU member states excelling in conditions for agricultural production are generally less efficient in getting Unitary Patents than other EU member states with similar GDP per capita, in particular, if these other states are close to the hub of the above-mentioned Scandinavian trio. However, it might be argued that having resources is futile without the determination and capacity to go for R&D, and so not only GDP per capita should be considered, but as well GERD and GERD Index.

GERD and Unitary Patents – commitment to patenting

As explained above, inventions and their patenting protection need both time and money. In particular, the time progression of the patenting process implies the appropriateness to work with GERD and GERD Index (percentage of R&D spending compared to GDP in 2019-2022) and the number of Unitary Patents as of 2024. In order to achieve an enhanced, revealing effect, the visualization of GDP per capita with the time evolution, is presented in Figure 3.

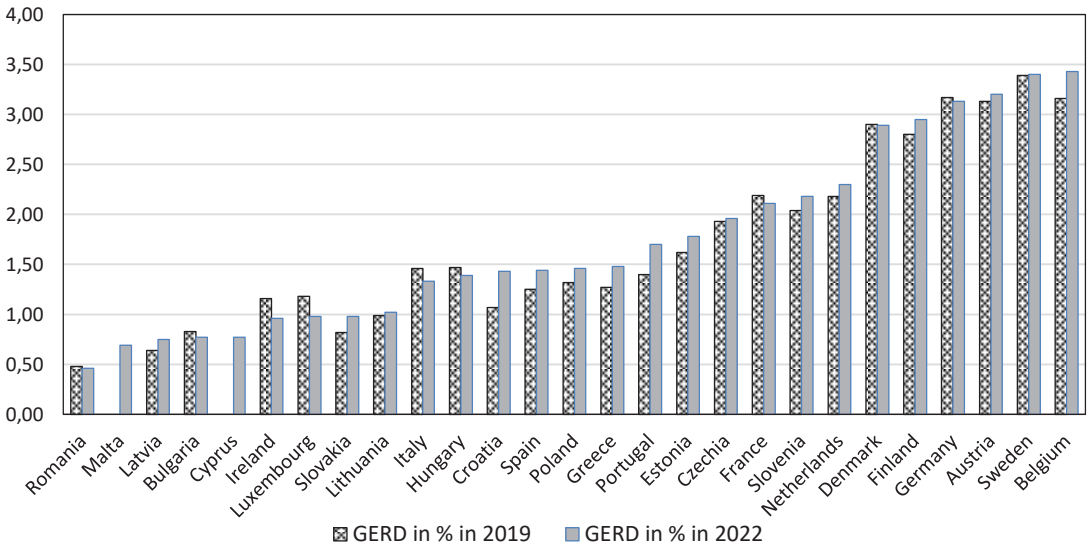

Figure 3. GERD in percentage of GDP aka GERD Index in 2019 and 2020 (all EU member states)
Source: Statista, Eurostat.

Similar to GPD per capita, no major changes occurred in GERD in EU member states between 2019 and 2022. Due to the lack of data about the GERD of Cyprus and Malta in 2019, the preceding statement should be taken with caution regarding these two jurisdictions. Despite this reserve, it is obvious that there are massive differences in GERD among EU member states, while the value for the first place, Belgium, is 7x higher than for the last place Romania. Again, generally, the West and North EU member states reach higher GDP per capita than the South and East EU member states. Considering the UPS and the full participation of 18 EU member states, it is relevant to mention that, as of 2022, only four EU member states had met the target of Europe 2020, i.e., only Belgium, Sweden, Austria and Germany reached the threshold of 3% of GERD Index, and that in the half of the EU member states with a higher GERD Index there are only (towards its end) two states not fully participating in the UPS (Czechia and Greece). This suggests that jurisdictions where the investment in R&D takes a larger part of GDP are, at the same time jurisdictions with a higher GDP per capita. Namely, it appears, prima facia, that West and North EU member states are richer, more committed to invest in R&D, and more pro-UPS. Rather unsurprisingly, the Figure below indicates that these GDP per capita and GERD Index winners are as well Unitary Patents winners (Table 4).

Table 4. Unitary Patents per millions of inhabitants b 1st June 2024 in EU member states with a high GERD Index in 2022

EU member state	Country Code	GERD Index in 2022	Number of UP per millions of inhabitants by 1st June 2024
Austria	AUT	3.20	98.13
Belgium	BEL	3.43	53.74
Denmark	DNK	2.89	147.45
Finland	FIN	2.95	111.51
France	FRA	2.11	33.23
Germany	DEU	3.13	72.47
Sweden	SWE	3.40	146.02

Source: Statista, Eurostat (GERD in 2022), EPO dashboard (Unitary Patents by 1st June 2024).

The same pattern and segregation occur for the number of Unitary Patents per million inhabitants, as in the case of GDP per capita, GERD, GERD Index, and even UPS full participation. The leadership of Northern EU member states regarding the density of Unitary Patents is obvious, and there is sparsity in the case of East and South EU member states without UPS full participation (Croatia, Slovakia, Poland, Greece, Hungary) and at the same time a lower GERD Index, i.e. under 2% (Table 5).

Table 5. Unitary Patents per millions of inhabitants by 1st June 2024 in EU member states with a lower GERD Index in 2022

EU member state	Country Code	GERD GERD Index in 2022	Number of UP per millions of inhabitants by 1st June 2024
Czechia	CZE	1.96	7.63
Estonia	EST	1.78	16.11
Greece	GRC	1.48	4.46
Hungary	HUN	1.39	5.42
Latvia	LVA	0.75	6.38
Lithuania	LTU	1.02	5.92
Poland	POL	1.46	4.17
Portugal	PRT	1.70	12.60
Slovakia	SVK	0.98	3.98

Source: Statista, Eurostat (GERD in 2022), EPO dashboard (Unitary Patents by 1st June 2024).

Therefore, a mere collection, the positioning of the data and the visualization support the intuitive suggestion that the higher economic wealth of the country and being committed to investing in R&D might have a positive effect on participation in the UPS and/or on the number of Unitary Patents. This immediately suggests considering other factors as well as, non-EU member states, i.e., to see whether the same applies to the biggest competitors of the EU and EU member states.

Comparative juxtaposition pointing to emerging clusters, pairs and trends

The above presented data suggest that there are massive differences in Unitary patenting per million of inhabitants, GDP per capita and GERD in EU member states and that at the same time there are no dramatic trend differences, i.e. in particular GDP per capita and GDP per capita, GERD and GERD Index have not has not changed dramatically in recent years in these jurisdictions. Further, data regarding the first 20 months of UPS operation suggests that the entire system magnifies differences, i.e. EU members states with a higher GDP per capita have as well a higher GERD Index (around 3%) and are more likely to be full members of UPS and getting more Unitary patents per million of inhabitants. This avalanche effect works as well in the opposite direction, i.e. a lower GPD per capita typically parallels with a lower GERD Index (under 2%) and with the absence of the full participation in the UPS and with a lower number of Unitary Patents per million of inhabitants. To put it differently, it appears GERD has a positive impact on the number of Unitary Patents, but its significance is not as strong as GDP per capita levels. Since the Scandinavian trio manages to achieve the desired threshold of 3%, it benefits from the double positive effect of a high GDP per capita and a high GERD Index. There are only three other EU member states getting close to or passing the 3% GERD Index threshold - Austria, Belgium and Germany, i.e., these three countries have as well a high GDP per capita, but their efficiency in getting Unitary Patents is lower; see below. This leads to questions – which EU member states have a high GDP per capita and a lower GERD Index, and how are they doing regarding efficiency in getting Unitary Patents? Such data is placed in the Table below by skipping small EU member states with few Unitary Patents in order to avoid random results, see Table 6.

Table 6. GDP, GERD, and Unitary Patents in EU member states with a higher GDP and a lower GERD Index

EU member state	Country Code	GDP per capita in euros in 2023	GERD in % of GDP aka GERD Index in 2022	Number of UP per millions of inhabitants
Czechia	CZE	29 180	1.96	7.63
France	FRA	41 330	2.11	33.23
Italy	ITA	35 350	1.33	29.75
Netherlands	NLD	59 710	2.30	64.54
Slovenia	SVN	29 750	2.18	28.29
Spain	ESP	30 320	1.44	12.17

Source: Statista, Eurostat, World Bank (GDP and GDP per capita in 2023), Eurostat (GERD in 2022), EPO dashboard (Unitary Patents).

This pool of six EU member states can be split into two sub-groups. The first one includes EU member states with a GERD Index in 2022 over 2%, and, interestingly enough, these three EU member states have as well a higher GDP per capita than the other EU member states with a GERD Index between 1.33% and 1.99%. The first sub-group is clearly more efficient in patenting than the second sub-group. However, it is worth observing that, within the first sub-group, two EU member states have a similar GERD Index and similar patenting efficiency, i.e., the number of Unitary Patents per million inhabitants, but dramatically different GDP per capita – EUR 41 330 (France) v EUR 29 750 (Slovenia). Hence, Slovenia is more efficient in turning the invested funds into patents than France. Further, it is worth observing that, within the second sub-group, two EU member states have similar GERD Index and even a rather similar GDP per capita and size (geographical + population), but their patenting efficiency is dramatically different – 29.75 (Italy) v 12.17 (Spain).

In sum, EU member states with at least an average GDP per capita and with at least an average GERD Index have more Unitary Patents per million inhabitants and arguably might be more efficient in getting them. However, this statement about the synergy effect of GDP per capita and GERD, which ultimately magnifies the differences between EU member states, can be expanded by a deeper and more individual look at these potential innovation and sustainability leaders and by addressing questions such as: Why are Scandinavian states doing so much better than the rest? Why are Austria, Germany and the Netherlands doing so much better than Belgium, France and Spain? Naturally, it is unrealistic to expect massive innovation, sustainability, and patenting effectiveness and efficiency from EU member states with low GPD, GDP per capita, and GERD. However, it is realistic to expect that more fortunate EU member states with a high GPD, GDP per capita, and GERD should excel and, potentially, they, along with the entire UPS, should help the, so far, less fortunate EU member states, see the principle of solidarity. Arguably, this is not the case and, as a matter of fact, certain alleged innovation, sustainability and patenting leaders appear to have lost their momentum and to be lagging even behind allegedly economically and otherwise weaker states – see the decline of France which, pursuant to the ongoing trend, should soon have even fewer Unitary Patents than Italy (France acquired 1238 Unitary Patents during 7 months in 2023 and only 1059 during the first 7 months in 2024, while Italy got 904 and 903) and this despite the much higher GDP, GDP per capita and GERD of France compared to Italy. Since even Germany is not excelling, it is not irrelevant to ask for the legitimacy and appropriateness of the German-French tandem to shape, if not dictate, the EU policies for innovations, sustainability and patenting … perhaps other nations should be given much more input about how to transform the money invested in R&D into innovations, and ideally into pro-sustainability and pro-competitiveness solutions protected by the European intellectual protection, in particular the industrial property protection *par excellence* – the Unitary Patents.

However, it cannot be overemphasized that these ideas are rather indicative suggestions and definitely are not solid and statistically robust conclusions. The UPS needs more years of operation and stable membership. In additon the inherent and overwhelming differences in GDP per capita and GERD between EU member states make conventional statistic comparision highly problematic, and this even if jurisdictions with GDP particularities and missing GERD data are omitted, i.e. financial sector oriented Luxembourg, modern tehnologies headquartering Ireland, and Malta. The below Table 7 demonstrates the disparities between the remaining 24 EU member states.

Table 7. Summary statistics for 24 EU member states

Variable	Mean	Standard Deviation	Minimum	Maximum
Unitary Patents per mil. Inhabitants as of 1st June 2024	37.75	45.99	0.37	147.4519
GDP per capita in euros in 2023	32,967.94	15,868.79	9,874.34	69,268.65
GERD in 2022	1.88	0.89	0.46	3.49

Source: Statista, Eurostat, World Bank (GDP per capita), EPO dashboard (Unitary Patents).

This suggests to depart from national particularies and consider the EU in its entirety and compare the nominal GDP in millions of USD, such GDP per capita, GERD, GERD Index and number fo Unitary Patents and Unitary Patents per million of inhabitants for the EU and its top four competitors, see the Table 8.

Table 8. GDP, GERD, and Unitary Patents in EU and selected non-EU states

State	Code	GDP (nominal) in millions of dollars in 2023	GDP per capita in dollars in 2023	GERD in % of GDP aka GERD Index in 2022	Number of UP per millions of inhabitants	Number of UP granted to July 26, 2024
EU	EU	18 349 388	40 697	2.24	38.96	17551
China	CHN	17 794 782	12 514	2.41	1.20	1 706
Japan	JPN	4 212 945	33 806	3.34	9.03	1 125
South Korea	KOR	1 712 793	35 569	4.93	21.58	1 039
USA	USA	27 360 935	81 632	3.46	13.73	4 601

Source: Statista, Eurostat, World Bank (GDP and GDP per capita in 2023), Eurostat (GERD in 2022), EPO dashboard. (Unitary Patents)

There are dramatic differences in GDP per capita (the GDP per capita in the US is 6x higher than in China), in GERD Index (the GERD Index of South Korea is 2x higher than that of the EU and GERD of the EU and China is similar!) and even in the number of United Patents per million inhabitants (32x higher in the EU than in China). However, it needs to be observed that these jurisdictions have different political and legal regimes and that, for various reasons, it might be better to use PCT patenting instead of EPO patenting with the European Patent or Unitary Patents. Consequently, the data placed in Table 8 should be considered with caution, and it needs to be kept in mind that they may easily lead to speculations and not academically robust conclusions. Thus, Table 8 should be rather appreciated as an illustration, perhaps an indication that GDP per capita and GERD might have a genuinely positive impact even if other than EU member states are considered; see the USA and South Korea and how they are overshadowing China and Japan.

Firstly, it should be emphasized the massive dominance of the GDP per capita of the USA, which is definitely not matched by the GERD Index dominance. Secondly, it is noteworthy the rather peculiar GERD Index position of the EU, which keeps very remote from the expected (and by its competitors predominantly achieved) milestone of 3%. To put it differently, the EU is not behind its competitors in terms of GDP per capita, but it is definitely behind in terms of GERD. The picture gets slightly more positive when the relative number of Unitary Patents is considered. This can be presented as supporting the relevance of the stated aims, especially of the GDP per capita on innovation protection (A1 and A2), in particular, if one patenting system for a set of states with the same regime is considered, i.e., the UPS. However, their empirical validity is a springboard for future longitudinal analyses and studies that could engage in multivariate regression analysis.

CONCLUSION

A theoretical background, framework setting and literature review demonstrate that inventions are typical intellectual property assets employed to resolve technical problems, and so are pivotal for improvements via innovations, which can boost competitiveness and support sustainability, in particular by finding new measures and avoiding waste. Inventions and innovations are critical for development, particularly sustainable development, and, at the same time, they are not easy to achieve, transposed in operation, and protected. They require creativity, determination, time, and resources.

The research utilized data collected from all EU member states regarding their GDP, GDP per capita, GERD, GERD Index, and number of Unitary Patents in total and per million inhabitants and explored the role of economic resources on the Unitary Patent levels. The so far available data about UPS suggests that EU jurisdictions keep their levels of GDP per capita and GERD, and generally, those with a higher GDP per capita are likely to have GERD Index, over 2% (preferably closer to 3% or over), are more likely to be full members of the UPS and their subjects are more likely to get Unitary Patents. Similarly, EU jurisdictions with a lower GDP per capita are likely to have a lower GERD Index (under 2%), not to be full members of the UPS and their subjects are less likely to get Unitary Patents. Nevertheless, the freshness of the entire UPS, the motions in its membership, the inherent patenting time delay, alternative options such as European patents and PCT, and massive cultural, social, and other differences between EU member states make conventional statistical, regression and modeling processing not robust at this point of time.

Nevertheless, despite these massive limitations, inevitable data shortage and a speculative time delay, the provided analysis has merits. In particular, the first step allows for moving on to a deeper appreciation of the interaction, mutual influence and impact of variables such as GPD/capita, GERD, GERD Index, and Unitary Patents per millions of

inhabitants. Further, it has the potential to induce thoughts about relevant economic and institutional factors and national particularities shaping the overall innovation ecosystem. The future studies should definitely focus on the Scandinavian trio, which appears to lead the way, while Austria and Germany do their best to follow and France and Belgium might have lost their momentum and might be passed by Italy, while for the Czechia and Poland, the situation looks even less promising. Further studies need to keep an eye on the top four competitors, while their conclusions in particular regarding GERD Index (China having more than EU!) and patenting, should promptly get out of the academia into the business universe and to policy and law makers.

In sum, UPS is operational and despite the joint institutional regime and setting, EU member states are heterogeneous in their resources, efficiency and UPS performance, while the top competitors use it along with other options. The pro-integration EU tandem – France and Germany – does not hold firmly the effectiveness and efficiency laurel wreath in this arena, and perhaps ideas about the setting and operating of the regime for inventions, innovations, and their patenting protection should come from places other than Berlin, Brussels and Paris, yet this would require more work in addressing the hot-spots, i.e., cities and regions with the most Unitary Patents, which could be subject of regional and spatial analysis. It might be enlightening to engage in more depth in the ephemeral relationship between inventions turned into innovations which enhance sustainability and competitiveness. Indeed, the search for roots and substrata causes that are promoting or inhibiting the drive for sustainability and innovation in the EU is critical, especially since the new European Commission of Ursula von der Leyen has as one of its three priorities "A prosperous and competitive Europe" The motto of the EU is "united in diversity" and this unification needs definitely to materialize in this arena in a smart, sustainable and respectful manner.

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Authorship contribution statement

Radka MacGregor Pelikánová: Concept, Search and Collecting Data, Methodology and Data Processing, Framework and Background Development, Writing Original Draft, Writing. **Martin Hála**: Search and Collecting Data, Methodology, Drafting. **Marek Beneš**: Framework and Background Development, Drafting.

Conflicts of interest

The authors declare no conflicts of interest.

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The Digital-Sustainability Ecosystem: A conceptual framework for digital transformation and sustainable innovation

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Abstract

PURPOSE: *This study introduces the Digital-Sustainability Ecosystem, a conceptual framework to integrate digital transformation and sustainable innovation. It examines how emerging digital technologies, including artificial intelligence, blockchain, and the Internet of Things, drive sustainability transitions by serving as strategic enablers. Addressing a critical gap in the literature, this research focuses on the dynamic mechanisms and synergies that connect digital transformation with sustainable innovation within a complex ecosystem.* ***METHODOLOGY:*** *The study employs a systematic literature review (SLR) of 50 studies and a comparative analysis of 13 existing frameworks to identify and analyze key mechanisms that link digital transformation and sustainable innovation, culminating in the development of the Digital-Sustainability Ecosystem framework.* ***FINDINGS:*** *The study identifies five interconnected mechanisms: efficiency gains, dematerialization, circular economy enablement, innovation acceleration, and digital collaboration. These mechanisms illustrate the relationships between technological advancements and sustainability objectives while addressing synergies and tensions, such as the trade-offs between energy demands and environmental benefits. The Digital-Sustainability Ecosystem emphasizes multi-stakeholder collaboration, iterative feedback loops, and adaptable processes to address gaps in existing models, positioning digital transformation as a transformative force for systemic sustainability improvements.* ***IMPLICATIONS:*** *The Digital-Sustainability Ecosystem advances theoretical discourse by positioning sustainability as a systemic outcome of digital transformation, extending beyond traditional efficiency-focused models. It emphasizes organizational resilience and stakeholder collaboration as pivotal for achieving sustainability objectives. Practitioners can leverage AI, IoT, and blockchain to enhance resource optimization and foster sustainability-driven innovation ecosystems. Policymakers and organizations are encouraged to combine digital strategies with sustainability imperatives, emphasizing adaptive leadership, regulatory alignment, and multi-stakeholder engagement.* ***ORIGINALITY AND VALUE:*** *This study presents a conceptual framework that bridges theoretical and practical gaps in the literature by integrating foundational theories that associate digital transformation with sustainability imperatives while fostering innovation and competitive advantage. The framework sets the stage for future research, emphasizing potential applications in industry-specific contexts, cross-sectoral collaborations, and the evolving role of emerging technologies in sustainability transitions. By incorporating dynamic feedback loops and systemic adaptability, this framework establishes a foundation for advancing both academic inquiry and practical implementation. It offers guidance for exploring unanswered questions about scalability, policy integration, and multi-stakeholder engagement in the digital age.*

Keywords*: digital transformation, sustainable innovation, digital-sustainability ecosystem, sustainability transitions, artificial intelligence, blockchain, Internet of Things, circular economy, efficiency gains, dematerialization, acceleration, digital collaboration, stakeholders*

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INTRODUCTION

The digital transformation, characterized by integrating cutting-edge digital technologies into organizational frameworks, has become a transformative force reshaping industries globally. Tools such as artificial intelligence, the Internet of Things (Gabsi, 2024), and blockchain (Omol, 2023; Pham et al., 2025) enhance operational efficiency and fundamentally redefine value-creation processes. Simultaneously, the global urgency for sustainable innovation has intensified, driven by the need to combat environmental degradation, resource scarcity, and social inequalities. These dual forces, digital transformation and sustainable innovation, offer the potential for profound synergy, yet their intersection remains underexplored. Despite advancements, a comprehensive understanding of how digital transformation acts as a catalyst for sustainable innovation is still lacking.

The COVID-19 pandemic has further accelerated the adoption of digital technologies, embedding them deeply into organizational and societal processes (Winarsih et al., 2021). This rapid shift underscores the potential of digital tools to address pressing environmental and social challenges through sustainability-driven innovation (Estrada & Reyes Álvarez, 2023). However, integrating digital transformation with sustainability objectives presents significant challenges. Existing frameworks often fall short of holistically balancing profitability, environmental stewardship, and social responsibility (Pappas et al., 2023). This fragmentation shows the need for comprehensive, integrative frameworks to align sustainability goals with digital transformation processes.

Although prior literature has extensively analyzed digital transformation as a technological and strategic phenomenon, focusing on aspects such as automation (Frank et al., 2019), decision-making (Korherr et al., 2022), and scalability (Thekkoote, 2022). Likewise, sustainable innovation has been analyzed through eco-efficiency (Dyck & Silvestre, 2018; Guo et al., 2020), circular economy (Al Halbusi et al., 2024), and stakeholder inclusivity (Ayuso et al., 2011). The intersection of digital transformation and sustainable innovation requires further exploration. Current research tends to be fragmented, primarily addressing individual mechanisms like resource optimization and waste reduction (Parolin et al., 2024). However, these studies overlook the complex, dynamic interactions between digital technologies and sustainability practices crucial for achieving comprehensive sustainability transitions. To advance understanding in this field, it is essential to consider the systemic interplay between these domains rather than viewing them in isolation.

This study seeks to address these gaps by constructing a conceptual framework, the Digital-Sustainability Ecosystem (DSE), which elucidates the interdependencies and synergies between digital transformation and sustainable innovation. Guided by two research questions (RQs), this study investigates:

RQ1: How can digital transformation be strategically aligned to enhance sustainable innovation within a Digital-Sustainability Ecosystem?

RQ2: What are the key mechanisms through which digital transformation drives the alignment between technological advancements and sustainability practices to achieve systemic and measurable sustainability outcomes?

Addressing these questions, the DSE framework captures the complexities of sustainability transitions through key technological, organizational, environmental, and societal dimensions while emphasizing mechanisms such as efficiency gains, dematerialization, circular economy enablement, innovation acceleration, and digital collaboration. The framework underscores the role of systemic interactions in fostering eco-innovation, optimizing resource use, and enhancing adaptability to changing environmental and market demands. In this context, "ecosystem" refers to the dynamic and interdependent relationships between digital technologies, organizational processes, natural environments, and socio-economic structures. These interactions form an integrated system that promotes resource optimization, innovation, and resilience.

To ground the DSE framework, this study synthesizes foundational theories, including dynamic capabilities (Teece et al., 1997), diffusion of innovation (Rogers, 1995), the resource-based view (Barney, 1991), sociotechnical systems (Baxter & Sommerville, 2011), and institutional theory (Meyer & Rowan, 1977). These theoretical approaches are integrated with sustainability-oriented concepts such as the triple bottom line (Elkington & Rowlands, 1999), circular economy principles (MacArthur, 2013), stakeholder theory (Freeman, 2010), and innovation systems (Lundvall, 1992). Stakeholder theory, while not inherently a sustainability-oriented concept, provides a lens for understanding how organizations can address diverse stakeholder needs and integrate these interests into sustainability strategies. Similarly, innovation systems emphasize the role of networks and institutions in fostering innovation, making them particularly relevant for advancing sustainability transitions by promoting collaboration and knowledge exchange.

This multi-theoretical approach underscores the systemic role of digital transformation in advancing sustainability objectives while addressing environmental impacts (Zulfiqar et al., 2023). According to the United Nations Environment Programme (UNEP, 2024), digital technologies can significantly contribute to achieving all 17 Sustainable Development Goals (SDGs). A total of 103 out of 169 SDG targets are directly influenced by a synergistic application of seven key digital technologies: digital access, high-speed Internet, cloud computing, the Internet of Things (IoT), artificial intelligence (AI), extended reality, and blockchain. These technologies enable advanced monitoring, promoting resource conservation, and influencing market dynamics and consumer behavior (Leal Filho et al., 2024).

A systematic literature review (SLR) of 50 studies and a comparative analysis of 13 frameworks underpin this research. Articles were identified through Scopus, focusing on peer-reviewed papers published between 2018 and 2024. This time frame ensures the inclusion of the most recent advancements in digital transformation and sustainable innovation, reflecting the rapid evolution of technologies and their integration with sustainability practices. The final selection of 50 studies resulted from a rigorous multi-stage filtering process, ensuring traceability in the search methodology and alignment with global sustainability goals. These findings contribute to the ongoing dialogue on fostering resilience and equity in the digital age.

This paper is structured as follows: the Theoretical Background section explores key concepts and definitions of digital transformation and sustainable innovation. The Methodology details the systematic literature review process. The Results and Discussion present the DSE framework, detailing its components, pathways, and implications for practice and policy. The Conclusion outlines the theoretical contributions, practical applications, and potential avenues for future research.

THEORETICAL BACKGROUND

Digital transformation

Digital transformation involves the integration of digital technologies into organizational processes and strategies, fundamentally altering the mechanisms through which organizations create value. It is a technological upgrade and a systemic reconfiguration encompassing strategic, cultural, and operational dimensions (Tebenko et al., 2024). At its core, digital transformation represents a fundamental rethinking of organizations leveraging digital platforms and advanced technologies to innovate. Key enablers include smart technologies, such as artificial intelligence, the Internet of Things (IoT), and big data analytics, enabling firms to harness modern systems' interconnectedness and intelligence (Tang, 2021). Within the concept of Industry 4.0, organizations integrate these technologies to enhance automation and robotization, driving efficiency, reducing costs, and improving decision-making capabilities (Małkowska et al., 2021).

Digital transformation extends beyond operational improvements, encompassing the creation of new revenue streams and scalability through the adoption of digital platforms (Yang et al., 2023). These platforms facilitate the creation of digital business models that transform traditional value chains and customer interactions by utilizing digital ecosystems (Aghazadeh et al., 2024). The concept of "ecosystem" plays a central role in this context, referring to complex, dynamic networks of interconnections between organizations, stakeholders, and their environments (Adner, 2006; Candelario-Moreno & Sánchez-Hernández, 2024). Borrowed from biology, the term underscores the interdependence and coevolution of entities within an integrated system (Tansley, 1935). In digital transformation, ecosystems facilitate resource sharing, collaboration, and innovation, fostering competitive advantage.

The literature provides various theoretical frameworks to understand the drivers and complexities of digital transformation. This study employs a multi-theoretical approach, synthesizing dynamic capabilities theory (Teece et al., 1997), diffusion of innovation (Rogers, 1995), resource-based view (Barney, 1991), sociotechnical systems (Baxter & Sommerville, 2011), and institutional theory (Meyer & Rowan, 1977). Each of these theories offers unique insights into the multidimensional nature of digital transformation, addressing both internal and external dynamics. Dynamic capabilities theory emphasizes organizations' strategic responses to rapidly changing environments, focusing on adaptability and resource alignment to harness external opportunities (Eisenhardt & Martin, 2000). In the context of digital transformation, this theory emphasizes the importance of building internal capabilities to integrate digital tools, realign processes, and reskill employees (Saputra et al., 2024; Warner & Wäger, 2019).

While dynamic capabilities explain the "how" of digital transformation, they do not sufficiently address diffusion and external acceptance of digital innovations. These aspects are better elucidated by the diffusion of innovation theory, which broadens the analysis to explain how innovations are adopted and diffused within and across industries (Rogers, 2003).

This theory examines how innovations spread across social systems, emphasizing the roles of adopters, communication channels, time, and social context (Vargo et al., 2020). Factors such as relative advantage, compatibility with existing systems, complexity, observability, and trialability are pivotal in accelerating or impeding adoption (Tornatzky & Klein, 1982). Regulatory pushes, environmental uncertainties, and informal inter-organizational networks further influence organizational readiness and adaptability and stress how political mandates and market expectations facilitate or hinder the assimilation of innovations (Greenhalgh et al., 2004). When applied to digital transformation, this theory provides a systemic understanding of why some organizations adopt digital technologies earlier than others. However, it treats innovation as a discrete process rather than a continuous, iterative transformation, limiting its ability to explain the long-term evolution of digital transformation (Schneider & Kokshagina, 2021).

Focusing solely on the adoption process also neglects the strategic leveraging of adopted technologies, an area more comprehensively addressed by the resource-based view (RBV). This theory emphasizes the role of unique and often intangible digital assets, such as data analytics, digital platforms, and technological expertise, as critical enablers of sustainable competitive advantage (Teece, 2007). The RBV frames digital resources as pivotal to achieving differentiation and efficiency, focusing on their strategic deployment to differentiate from competitors (c.f., Rumelt, 1984). However, the RBV's inward orientation often underestimates the dynamic and ecosystemic nature of digital resources, which are interdependent and frequently evolve beyond firm-specific boundaries. Furthermore, the RBV often overlooks the interplay between technological and human factors essential for successful digital transformation. Sociotechnical systems theory addresses this gap, highlighting the interdependence of technological and human dimensions in organizational change (Appelbaum, 1997).

Sociotechnical systems theory provides a holistic perspective by emphasizing the alignment of digital tools with organizational culture, skills, and workflows (Sony & Naik, 2020). For instance, the successful implementation of artificial intelligence (AI) or cloud computing often hinges on technical functionality, employee acceptance, ethical considerations, and organizational readiness. This theory underscores the need for buy-in from key stakeholders and adaptable organizational structures to ensure the success of technological initiatives. However, while it effectively addresses internal dynamics, sociotechnical systems theory does not sufficiently account for external pressures and institutional dynamics that influence transformation processes.

In line with institutional theory, organizations frequently undertake digital transformation as a response to three forms of institutional pressure. First, coercive pressures (e.g., digital regulations or mandatory standards) compel compliance to maintain legitimacy and avoid sanctions (DiMaggio & Powell, 1983; Scott, 2013). Second, mimetic pressures (e.g., adopting industry-standard technologies or imitating digitally advanced peers) arise under uncertainty, prompting firms to emulate perceived exemplars (Berrone et al., 2013; Wang et al., 2018). Third, normative pressures (e.g., professional norms or best practices favoring digital fluency) reflect broader societal and occupational expectations, leading organizations to align with prevailing digital standards (Meyer & Rowan, 1977; Zhang et al., 2023)

These theories converge to provide a multifaceted understanding of digital transformation. The strategic alignment and resource deployment described by dynamic capabilities and the RBV are complemented by the systemic and external considerations of diffusion of innovation and institutional theory. Despite their contributions, none of these theories fully capture digital transformation's systemic and iterative nature. Dynamic capabilities and RBV focus heavily on internal organizational capabilities, often overlooking broader ecosystemic dynamics. Diffusion of innovation theory lacks depth in explaining strategic and adaptive processes, while sociotechnical systems theory and institutional theory address contextual factors but inadequately link them to competitive outcomes. It becomes evident that digital transformation is not a linear process but a dynamic and iterative reconfiguration of organizational capabilities and interactions within broader ecosystems.

Sustainable innovation

Sustainable innovation refers to the creation of products, processes, or business models that generate economic value while fostering positive environmental and societal impacts. It represents a fundamental shift from traditional profit-centric innovation to approaches grounded in eco-efficiency and social equity (Varadarajan, 2017). Bocken et al. (2016) describe sustainable innovation as a reconfiguration of business practices that optimize resource use, reduce waste, and deliver systemic environmental and social benefits, thereby positioning firms as proactive contributors to sustainable development. Often referred to as eco-innovation or environmental innovation, sustainable innovation focuses on reducing ecological footprints, enhancing social value, and ensuring economic viability.

A key dimension of sustainable innovation lies in its alignment with circular economy principles, emphasizing resource efficiency, waste minimization, and establishing closed-loop systems (Hapuwatte & Jawahir, 2021). This involves designing innovations that extend product lifecycles, enable recycling, and optimize resource use, thereby decoupling economic growth from environmental degradation. Sustainable innovation also drives competitiveness, enabling firms to meet regulatory demands, respond to shifting consumer preferences for sustainable products, and achieve cost reductions through enhanced efficiency (Voegtlin & Scherer, 2017). Distinctive forms of sustainable innovation, such as green innovation (Afeltra et al., 2023; Ibarra-Cisneros et al., 2024), low-carbon innovation (Shi & Lai, 2013), and sustainability-driven innovation, each reflecting specific dimensions of sustainability goals (Shi & Lai, 2013). Green innovation encompasses innovations that reduce environmental impacts, including a broad range of technologies and processes for environmental protection and resource efficiency (Leal-Millan et al., 2017). Low-carbon innovation targets greenhouse gas emission reductions through energy-efficient technologies, sustainable transportation, and carbon-neutral solutions (Ma, 2024). Sustainability-driven innovation involves the development of new or improved products, services, or processes aimed at decreasing the consumption of natural resources and reducing the emission of harmful substances into the environment. This concept adopts a holistic approach by considering the entire lifecycle, design, production, use, and end-of-life stages to minimize environmental impact (Hansen & Grobe-Dunker, 2013).

At the organizational level, sustainable business models embed sustainability into core strategic priorities, fostering long-term value creation (Achtenhagen et al., 2013). Such models enable resource efficiency, ensure optimal utilization of natural and financial resources, and support firms in mitigating environmental impacts while maintaining economic growth. These dimensions position sustainable innovation as a transformative approach to achieving global sustainability objectives and fostering resilient economic systems (Inigo & Albareda, 2016). As an interdisciplinary concept, sustainable innovation integrates environmental, social, and economic dimensions of sustainability, reflecting the increasing awareness of global challenges such as climate change, resource depletion, and social inequalities (Adams et al., 2016). This growing awareness has driven scholars and practitioners to reconfigure innovation frameworks, balancing competing priorities and fostering equitable and sustainable development.

The triple bottom line (TBL) provides a foundational framework for sustainable innovation, emphasizing that organizational performance must simultaneously account for environmental integrity, social equity, and economic viability (Elkington, 1998; Weidner et al., 2021). Encapsulated as the "3Ps" (Planet, People, and Profits), the TBL challenges traditional profit-driven models by addressing interdependencies among these dimensions. Innovations that reduce carbon emissions or improve energy efficiency exemplify the alignment of economic and environmental goals, while social innovations promoting inclusivity and equitable resource access reinforce the social pillar. However, critiques of the TBL underscore its limitations in operationalizing and quantifying the synergies and trade-offs among the three dimensions (Wu et al., 2024).

Stakeholder theory complements the TBL by emphasizing multi-stakeholder engagement in shaping sustainable innovation pathways (Freeman, 2010). Stakeholder collaboration is crucial for the co-creation and legitimacy of innovation outcomes, addressing systemic issues such as resource inefficiency and waste generation (Kazadi et al., 2016). For instance, incorporating consumer feedback into product development ensures higher market acceptance for sustainability-driven innovations. While stakeholder theory highlights the participatory aspects of sustainable innovation, challenges such as power imbalances, conflicting interests, and network complexity necessitate systemic approaches that account for broader institutional and structural influences.

Innovation systems theory provides a systemic perspective, emphasizing the interconnectedness of actors, institutions, and infrastructures in fostering sustainability transitions (Asheim et al., 2011). This approach is especially significant in the development of renewable energy technologies, where the interplay of institutional frameworks, financial resources, and knowledge networks collectively shapes the paths of innovation. Additionally, Innovation systems theory examines the spatial and sectoral dynamics of influence innovation, emphasizing how regional clusters, industry standards, and policy measures impact sustainability-focused innovation ecosystems. By integrating these systemic elements with normative frameworks like circular economy principles, we can enhance the practical application of sustainable innovation strategies.

The circular economy fundamentally transforms value creation frameworks by emphasizing resource optimization, waste reduction, and the establishment of closed-loop systems (Geissdoerfer et al., 2017). This paradigm shift is exemplified through advancements in recycling technologies, material substitution strategies, and the adoption of product-service systems, all of which work to minimize environmental impacts while generating economic returns. By prioritizing sustainability and a systemic approach to change, the circular economy aligns with the objectives of the TBL and offers

a comprehensive analysis through the lens of innovation systems theory. However, the path to achieving true circularity is fraught with challenges such as technological lock-ins, regulatory mismatches, and consumer pushback. This complexity underscores the necessity for integrated strategies that reconcile these theoretical frameworks and facilitate the transition toward circularity.

Sustainable innovation is a complex concept that requires comprehensive frameworks to balance economic goals with environmental and social objectives. The integration of the Triple Bottom Line (TBL) benchmarks, the participatory principles of stakeholder theory, the systemic analysis of innovation systems theory, and the practical approach of circular economy lay a strong foundation for promoting sustainable innovation. To effectively address the theoretical and practical challenges of aligning these perspectives, further cross-disciplinary collaboration is necessary to create scalable solutions.

METHODOLOGY

This research employs a Systematic Literature Review (SLR) to critically synthesize and analyze existing studies on the relationship between digital transformation and sustainable innovation. The SLR methodology was selected for its structured, transparent, and replicable nature in accordance with established guidelines (Snyder, 2019; Tranfield et al., 2003). The objective is to identify the mechanisms through which digital transformation influences sustainable innovation and develop a conceptual framework grounded in relevant theories. Figure 1 visually summarizes the systematic progression from defining the research objective to constructing the conceptual framework.

Search strategy and screening

The SLR was conducted using the Scopus database to ensure high-quality, peer-reviewed academic sources. An initial search using the keywords "digital transformation" AND "sustainable innovation" within the title, abstract, or keywords yielded 43 articles. To capture a broader scope of digital technologies relevant to sustainable innovation, additional search terms were applied based on their definitions and contexts presented in the Theoretical Background section: ("digital transformation" OR "digital technolog*" OR "digital platform" OR "artificial intelligence" OR "AI" OR "Industry 4.0" OR "smart technolog*" OR "digital business model" OR "automation" OR "robotization") AND ("sustainable innovation" OR "eco-innovation" OR "circular economy" OR "green innovation" OR "sustainability-driven innovation" OR "low-carbon innovation" OR "environmental innovation" OR "sustainable business model" OR "resource efficiency"). This expanded search generated a total of 3,370 articles.

A systematic filtering process was then applied to refine the dataset, ensuring relevance and quality: (1) Publication date: Articles published between 2015 and October 2024 were considered to capture both foundational and recent developments; (2) Document type: Only peer-reviewed journal articles and review papers were selected, ensuring the dataset's academic rigor; (3) Subject Areas: The search was limited to Business, Management and Accounting, Environmental Science, Social Sciences, Engineering, and Decision Sciences; (4) Language: Articles were restricted to English; (6) Publication stage: Only articles in their final publication stage were included to avoid incomplete or preliminary studies. These primary filters reduced the dataset to 1,420 articles.

Given the need for a focused and thematically relevant dataset, an additional refinement phase was applied: (1) Years: The dataset was narrowed to 2018-October 2024 to prioritize recent advancements while preserving theoretical depth and contemporary relevance; (2) Title keyword requirement: The search terms "digital transformation" and "sustainable innovation" were required in the article title to ensure primary relevance to the study's focus and reducing peripheral studies; (3) Subject areas: The search was further restricted to Business, Management, Accounting, and Environmental Science to align with the study's core research theme. Figure 1 provides a structured visualization of this stepwise selection process.

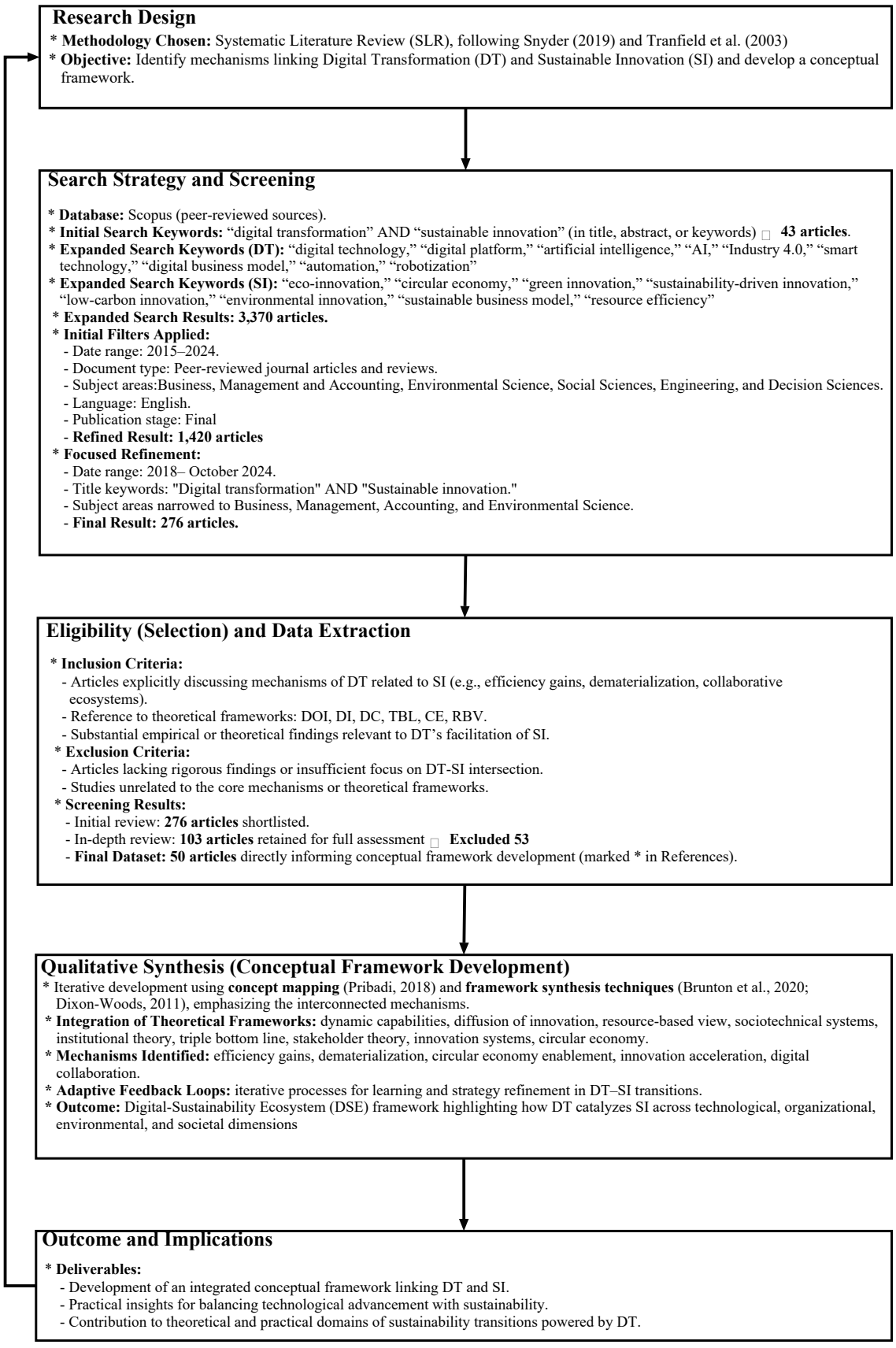

Figure 1. Methodological process for developing the digital-sustainability ecosystem conceptual framework

Eligibility (selection) and data extraction

The refinement process identified 276 articles for further screening, followed by a systematic eligibility review using predefined inclusion and exclusion criteria to ensure conceptual rigor and methodological precision. Studies were included if they: (1) Explicitly discussed mechanisms linking digital transformation to sustainable innovation; (2) Referenced key theoretical frameworks such as dynamic capabilities, diffusion of innovation, resource-based view, sociotechnical systems, institutional theory, triple bottom line, stakeholder theory, innovation systems, and circular economy; or (3) Provided substantial findings on digital transformation's role in facilitating sustainable innovation. In contrast, articles were excluded if they: (1) Lacked sufficient empirical findings on the digital transformation–sustainable innovation nexus; (2) Made only marginal references to these concepts without substantive theoretical contributions; or (3) Were not relevant to mechanisms or conceptual models. Following this rigorous screening, 103 articles underwent full-text assessment, leading to the exclusion of 53 articles. The final dataset consisted of 50 articles, which directly supported conceptual framework development (marked * in References). Within these 50 articles, 13 frameworks were identified for comparative analysis in the final section.

Qualitative synthesis (conceptual framework development)

The Digital-Sustainability Ecosystem conceptual framework was developed through a qualitative synthesis approach, integrating systematic literature review (SLR) findings with established theoretical foundations. This iterative process identified and structured key mechanisms, pathways, and outcomes that characterize digitally-driven sustainable innovation. A comparative analysis of the 50 selected studies led to the identification of five interrelated mechanisms mediating the relationship between digital transformation and sustainable innovation. These mechanisms were further refined through conceptual mapping and systematically cross-referenced with empirical findings and theoretical constructs to ensure both conceptual coherence and empirical validity. To ensure methodological robustness, the framework was developed using concept mapping (Pribadi, 2018) and framework synthesis techniques (Brunton et al., 2020; Dixon-Woods, 2011). These methodological tools enabled a structured integration of theoretical and empirical insights, reinforcing the framework's academic rigor and practical applicability.

RESULTS AND DISCUSSION

The integration of digital transformation and sustainable innovation

Digital transformation and sustainable innovation are pivotal in contemporary organizational strategy and societal development. The intersection of these concepts is central to debates regarding the application of digital technologies to achieve sustainable outcomes. Research in this area has revealed both opportunities and complexities. The literature indicates that digital transformation catalyzes sustainable innovation by facilitating the development of sustainable business models (Li et al., 2023), optimizing resource use (Liang & Sun, 2024), and enhancing stakeholder engagement (Hallioui et al., 2022). Key technologies identified as drivers in this process include the Internet of Things (IoT), artificial intelligence (AI), blockchain, and big data analytics, which have been recognized as primary enablers of sustainable innovation (Belhadi et al., 2022; Wang et al., 2023b). IoT facilitates real-time energy consumption monitoring, helping firms reduce their carbon footprint, while AI-driven predictive analytics enhances decision-making by optimizing resource allocation, extending asset lifecycles, and minimizing waste in manufacturing and energy sectors (Yuan & Pan, 2023a; Li et al., 2024). These technologies enable operational efficiency and create new value propositions in response to the increasing demand for sustainability in global markets. Adaptability is critical in industries facing stringent regulatory requirements, where resilience must be maintained while pursuing sustainability-oriented goals (Lin et al., 2024). AI and IoT-based precision technologies in agriculture minimize resource inputs, such as water and fertilizers, while enhancing environmental outcomes (Ali & Johl, 2023).

These applications illustrate how dynamic capabilities empower firms to integrate emerging technologies into circular economy practices, creating closed-loop systems that reduce resource waste and environmental harm (Ren et al., 2024). For instance, blockchain-enabled supply chain systems enhance collaborative innovation by improving transparency, trust, and accountability among stakeholders (Saberi et al., 2019). Such integration generates long-term strategic value by aligning technological advancements with environmental goals, establishing a basis for sustained competitive differentiation and

leadership in sustainable innovation (Ammar et al., 2024). Scholars have emphasized the role of digital platforms in fostering cross-sector collaboration and knowledge-sharing, enabling businesses, governments, and non-profits to co-develop sustainability solutions through open innovation mechanisms (Arroyabe et al., 2024; Liang & Sun, 2024). This interconnectedness promotes a systemic approach to innovation, with digital transformation as the foundation for scaling and integrating sustainable practices across industries and supply chains.

Despite its transformative potential, digital transformation faces adoption barriers, particularly in developing regions, due to high implementation costs, inadequate infrastructure, and limited digital literacy. These financial and technological constraints disproportionately impact smaller organizations, limiting their ability to integrate sustainability-driven innovations (Trevisan et al., 2023). Regulatory gaps and misaligned incentives further intensify these challenges, discouraging investments in technologies that promote sustainable innovation (Kumar et al., 2021). While digital technologies enable sustainability-oriented transformations, their high energy consumption, particularly in data centers and blockchain applications, raises concerns. To address this paradox, scholars advocate for "green digital transformation," in which digital adoption is explicitly designed to minimize environmental impact (Dong et al., 2024).

Companies pursuing sustainable innovation must incorporate long-term environmental and social considerations into their strategic and operational frameworks, prioritizing systemic transformation over incremental improvements (Neri et al., 2023). Wu et al. (2016) argued that the traditional focus on economic, environmental, and social factors inadequately captures the complexity of sustainability. They advocated incorporating additional dimensions such as operations, resilience, and stakeholder engagement. Tseng (2017) similarly emphasized that effective sustainability strategies necessitate integrating qualitative insights, quantitative data, and technological advancements within the Triple Bottom Line (TBL) framework. The "overlapping bottom line" model proposed by Wu et al. (2018) integrates dimensions like eco-efficiency, socio-economic, and socio-environmental benefits, suggesting that digital technologies can enhance co-benefits across these areas. Emerging tools such as AI, IoT, and blockchain further enhance the relevance of TBL by enabling firms to monitor and optimize sustainability metrics in real-time, thereby improving resource efficiency, regulatory compliance, and equity-driven outcomes (George et al., 2021).

Successfully integrating digital transformation with sustainable innovation necessitates organizational adaptability. Firms that cultivate a culture of continuous improvement, supported by strategic leadership and stakeholder engagement, enhance resilience and long-term sustainability (He et al., 2024; Lin et al., 2024). Additionally, studies emphasize the importance of regulatory frameworks and policy interventions in ensuring digital transformation aligns with sustainability objectives (Akhtar et al., 2024). Governments and international organizations are increasingly promoting standards and incentives to encourage the adoption of technologies that support environmental and social well-being.

Recent advancements in digital technologies are expanding avenues for sustainable innovation in agriculture (Ali et al., 2024) and manufacturing (Lin & Xie, 2024; Schöggl et al., 2023). In agriculture, precision farming technologies employing IoT and drones enhance productivity while reducing resource inputs. In manufacturing, digital twins and 3D printing transform production processes by minimizing material waste and enabling localized production. These sector-specific innovations demonstrate how digital transformation supports sustainable development.

The literature emphasizes a systemic perspective to understand the link between digital transformation and sustainable innovation. Rather than viewing these concepts in isolation, scholars advocate for an integrative approach that considers the interdependencies among technological, economic, and social systems. Digital transformation is both a tool and a process that enhances the impact of sustainable innovation by fostering collaboration. Conversely, sustainable innovation guides digital transformation toward long-term value creation rather than short-term gains. The relationship is synergistic and complex, characterized by mutually reinforcing dynamics and inherent tensions. While digital technologies facilitate sustainability changes, effective implementation necessitates strategic alignment, cultural readiness, and supportive policy environments. Researchers and practitioners face the ongoing challenge of navigating this interplay to maximize digital transformation's potential as a catalyst for sustainable innovation, ensuring that technological progress leads to tangible and equitable benefits for society and the environment.

Key mechanisms driving sustainable innovation through digital transformation

Integrating digital transformation with sustainable innovation has led to the emergence of five interconnected mechanisms. The first mechanism, efficiency gains, enables organizations to optimize resource consumption, enhance operational resilience, and minimize waste, therby advancing sustainability objectives while maintaining productivity (Okorie et al., 2023). Advanced digital technologies facilitate these improvements through real-time data analytics, AI-

driven automation, and predictive maintenance, enabling organizations to proactively address inefficiencies (Qian & Chen, 2024). AI-driven predictive maintenance, for instance, extends machinery lifecycles, reduces unexpected downtime, and optimizes material usage directly contributing to eco-efficiency (Rajput & Singh, 2020). These optimizations align with circular economy (CE) principles, reinforcing digital transformation's role in fostering sustainable resource utilization (Zhao & Fang, 2023). Siemens has pioneered smart grid systems that dynamically adjust energy distribution, optimizing electricity flows and reducing carbon emissions in real-time (Oral et al., 2022; Siemens, 2024). As a result, efficiency gains serve as a core enabler of organizational adaptability, allowing firms to navigate evolving regulatory landscapes and align operations with global sustainability targets (Yuan & Pan, 2023b).

The second mechanism is dematerialization, which reduces material dependency by replacing physical products and services with digital alternatives, significantly lowering environmental impact (Zhang et al., 2024). Cloud computing exemplifies this shift by minimizing the need for on-site data storage, thereby reducing energy-intensive hardware reliance (Paredes-Frigolett & Pyka, 2023). This transition optimizes resource allocation and enhances eco-efficiency, particularly in manufacturing and logistics, where automated systems reduce material waste (Ahmad et al., 2023). The shift to digital services also reduces reliance on physical transportation and storage, reinforcing circular economy (CE) principles and enhancing sustainability outcomes (Toșa et al., 2024). This transformation is particularly evident in the manufacturing and media sectors, where automation, digital platforms, and service-based models replace traditional product-centric approaches (Ranta et al., 2018). 3D printing facilitates localized, on-demand production in manufacturing, reducing material waste and optimizing resource allocation (Lodha et al., 2023). Digital twins replicate physical assets in virtual environments, enabling manufacturers to conduct real-time monitoring, predictive simulations, and process optimizations, minimizing material consumption and improving lifecycle efficiency (Attaran et al., 2023). This is particularly relevant in resource-intensive industries such as automotive and aerospace, where AI-driven digital twins refine designs, optimize production cycles, and extend asset longevity, contributing to eco-efficiency and cost reduction (Ranta et al., 2018).

A third mechanism involves integrating CE principles through digital tools, where IoT and blockchain technologies facilitate real-time materials tracking, resource reuse, remanufacturing, and recycling processes (Agrawal et al., 2022; Yin, 2023). The core CE principles underpin this transition by eliminating waste and pollution, keeping materials in circulation, and regenerating natural systems (Kottmeyer, 2021). For example, the automotive and electronics industries leverage IoT-enabled sensors and blockchain-based material tracing systems to improve supply chain accountability, ensuring the efficient reuse and recycling of resources (Ranta et al., 2018). Innovative CE models, such as textile upcycling initiatives, are redefining product design strategies to enhance recoverability and recyclability (Lombardi Netto et al., 2021). Industry 4.0 advancements, including AI-driven analytics and cloud-based systems, further optimize CE implementation by enhancing process transparency, improving waste management, and reducing resource intensity (Gupta et al., 2021; Ghobakhloo et al., 2021). Blockchain technology plays a pivotal role in these developments, enabling secure, immutable records of material flows, ethical sourcing verification, and reducing inefficiencies in circular supply chains (Schöggl et al., 2023). However, concerns remain regarding the socio-cultural implications of blockchain standardization, as regulatory and economic disparities may disproportionately impact specific regions (Kottmeyer, 2021). Despite high transaction costs, limited secondary material data, and inefficient product design, digital transformation mitigates these barriers by enhancing supply chain transparency and facilitating collaborative decision-making (Kumar et al., 2024; Truant et al., 2024).

Digital transformation also fosters collaborative innovation ecosystems, where digital platforms function as enablers of stakeholder partnerships, resource-sharing networks, and cross-industry synergies (Li et al., 2023; Wang et al., 2023a). For example, blockchain-enabled knowledge-sharing hubs allow firms to co-develop sustainability solutions, optimizing resource utilization and waste reduction strategies (Wang et al., 2023a). These platforms facilitate transparent data flow, allowing stakeholders to engage in real-time decision-making and accountability. These ecosystems enhance multi-stakeholder collaboration through real-time data transparency, supporting scalable sustainability transitions across industries (Calabrese et al., 2021; Zhu et al., 2024). Additionally, AI-powered open innovation platforms aggregate diverse stakeholder insights, including corporations, policymakers, and researchers, accelerating breakthrough innovations in eco-efficient supply chain management and CE implementation (Wang et al., 2023b). Beyond industry applications, digital collaboration platforms also address regional disparities in technology adoption. Research indicates that digital innovation hubs in emerging economies have improved access to sustainability-driven technologies, facilitating localized solutions tailored to unique environmental challenges (Du & Jian, 2024). This highlights the broader role of digital transformation in bridging technological divides and promoting equitable access to sustainable innovation strategies. Furthermore, intersectoral digital collaboration fosters accelerated innovation adoption, reinforcing the critical role of cross-industry partnerships in scaling sustainability-driven initiatives (Arroyabe et al., 2024; K. He & Chen, 2024; Tao et al., 2024).

The five mechanisms, efficiency gains, dematerialization, CE adoption, innovation acceleration, and digital collaboration, form the foundation of our conceptual framework, illustrating how digital transformation catalyzes sustainable innovation. However, effectively translating these mechanisms into strategic initiatives requires considering contextual factors, including regulatory frameworks, market incentives, and organizational readiness.

Conceptual framework: Digital transformation as a catalyst for sustainable innovation

The Digital-Sustainability Ecosystem (DSE) conceptual framework positions digital transformation (DT) as a critical enabler of sustainable innovation (SI) (Figure 2). At the core of this framework lies the Digital-Sustainability Ecosystem (DSE), where DT and sustainability practices dynamically interact. The framework identifies three core components: Inputs, Pathways, and Outputs, moderated by external factors such as regulatory frameworks, market trends, and societal expectations. These components form adaptive feedback loops, reinforcing DT's role in fostering long-term sustainability transitions through continuous technological advancements, organizational learning, and external pressures. This systemic approach integrates technological, organizational, environmental, and societal dimensions, offering a holistic structure for embedding sustainability in digital strategies.

Inputs include technological and organizational capacities underpinning DT-driven sustainability efforts. The technological dimension encompasses AI, IoT, blockchain, big data analytics, and automation, enabling real-time data processing, resource optimization, and predictive analytics. The organizational dimension emphasizes adaptive leadership, agile structures, and cross-functional collaboration, ensuring DT adoption aligns with sustainability imperatives. Adaptive leadership facilitates regulatory navigation and strategic agility, while agile structures enable firms to rapidly integrate digital tools into sustainability-driven business models. These Inputs, therefore, demonstrate how firms must simultaneously develop technological and organizational capabilities to drive systemic, sustainable innovation (Bag, Yadav, et al., 2021; Ghobakhloo et al., 2021).

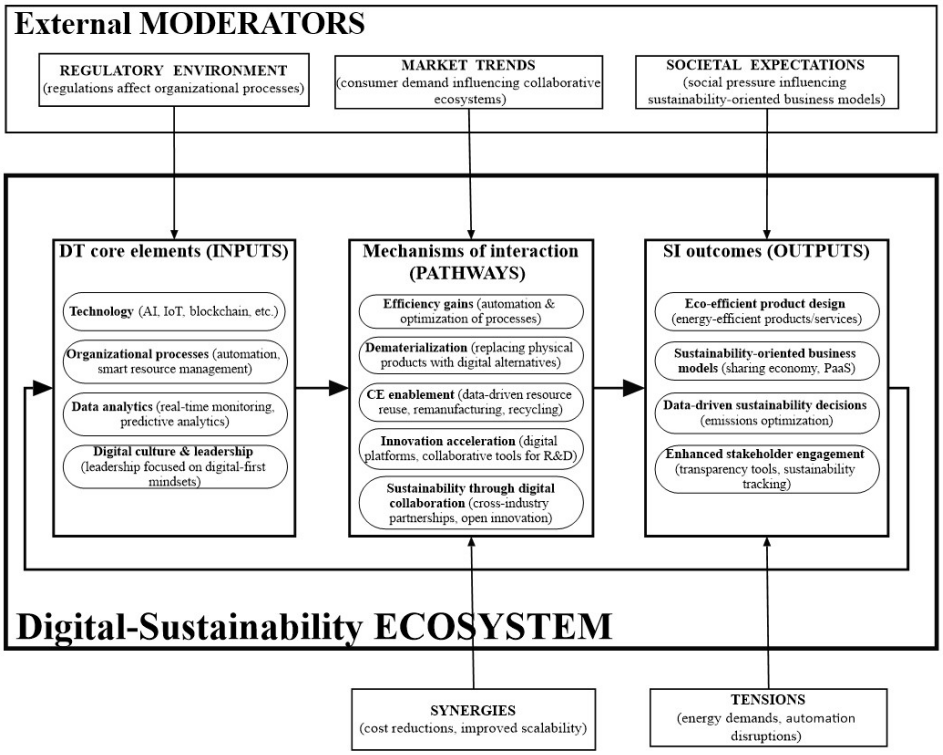

Figure 2. Conceptual Framework of the Digital-Sustainability Ecosystem (DSE)

The framework's Pathways outline how DT converts Inputs into sustainable innovation (SI) Outputs through five interrelated mechanisms: efficiency gains, dematerialization, CE enablement, innovation acceleration, and digital collaboration. These pathways align with the technological, organizational, and environmental dimensions, demonstrating

how diverse mechanisms interact within the DSE. Efficiency gains, facilitated by AI and IoT, optimize resource allocation and waste reduction. Dematerialization replaces physical products and services with digital alternatives, such as cloud computing and digital twins, minimizing material dependency and environmental impact. The CE enablement supported by blockchain and IoT enhances traceability, fostering closed-loop production systems prioritizing recycling and remanufacturing. Innovation acceleration, driven by digital platforms, fosters collaboration across diverse stakeholders, leveraging AI and crowdsourcing to expedite sustainability solutions aligned with the Triple Bottom Line (TBL) (Agrawal et al., 2022; Ghobakhloo et al., 2021; Schöggl et al., 2024; Tao et al., 2024). Multi-stakeholder digital collaboration, supported by blockchain-enabled transparency, facilitates strategic partnerships among various sectors, including industry, government, academia, and civil society. This systemic collaboration aligns disparate organizational priorities with shared sustainability objectives, ensuring scalability and risk-sharing in sustainability transitions.

The Outputs of the DSE encompass the tangible sustainability benefits derived from integrating DT with SI. These outcomes span environmental and societal dimensions, reinforcing DT's transformative role in shaping sustainable business practices. AI-driven eco-efficient product design reduces material waste and optimizes circularity throughout product lifecycles (Xiao et al., 2024b). Sustainability-oriented business models, such as product-as-a-service (PaaS), decrease resource dependency and embed CE principles into systemic practices, addressing both environmental and societal goals (Khan et al., 2021). Big data-driven decision-making facilitates real-time emissions monitoring, resource optimization, and compliance with sustainability policies, ensuring operational sustainability (Ali & Johl, 2023). Enhanced stakeholder engagement emerges from transparency-driven digital platforms, fostering multi-actor collaboration to align corporate strategies with sustainability regulations and societal demands (Li et al., 2023). Together, these outputs emphasize DT's systemic impact in reinforcing sustainability-driven innovation.

The DSE framework incorporates external factors that influence the role of DT in advancing sustainability. These factors, including regulatory frameworks, market trends, and societal expectations, represent the social dimension of the DSE and underscore the impact of external pressures on sustainability. Regulatory initiatives, such as the European Green Deal, exemplify the increasing societal emphasis on sustainability, establishing ambitious environmental goals and incentivizing businesses to adopt eco-friendly practices (European Commission, 2021). Financial incentives and compliance requirements drive organizations to implement technologies like IoT for emissions monitoring and AI for optimizing energy efficiency (Kumar et al., 2021). Market forces also play a decisive role in sustainability transitions. Consumers' growing preference for environmentally responsible products compels businesses to innovate their operations and business models. Additionally, investors, employees, and non-governmental organizations (NGOs) elevate these pressures by demanding greater transparency and accountability and demonstrating sustainability progress. This complex interplay among policy mandates, market expectations, and societal demands emphasizes the societal dimension of the DSE, and illustrates how external forces drive systemic sustainability transformations (Bag, Pretorius et al., 2021; Ren et al., 2024).

Beyond external pressures, the DSE framework addresses the synergies and tensions firms encounter when integrating digital transformation with sustainable innovation. Synergies emerge when advanced technologies enhance operational efficiency, reduce costs, and scale sustainability initiatives. However, tensions arise from trade-offs between digital infrastructure expansion and sustainability objectives. For instance, the high energy demands of AI and blockchain technologies present challenges to carbon neutrality unless paired with renewable energy solutions (Li et al., 2024). Financial constraints further complicate adoption, as firms must justify the substantial upfront investment costs against uncertain long-term sustainability benefits. This challenge is particularly pronounced in resource-constrained industries, where balancing profitability and sustainability commitments remains a strategic dilemma (Kottmeyer, 2021). Integrating digital transformation necessitates significant organizational restructuring, including workforce reskilling and process reconfiguration. While these adjustments are essential for leveraging digital capabilities, they can delay the immediate realization of sustainability benefits (Lin et al., 2024; Wang et al., 2023a).

The DSE framework incorporates an adaptive feedback loop to address these challenges, ensuring continuous sustainability improvements through iterative learning and strategic recalibration. IoT-enabled monitoring systems provide real-time environmental data, allowing firms to reassess and refine sustainability strategies. Concurrently, organizational learning mechanisms enable firms to integrate past insights into future strategies, fostering adaptability and resilience. External pressures, such as shifting regulations and evolving consumer expectations, are systematically incorporated into the loop, ensuring firms remain responsive to sustainability initiatives. This iterative cycle strengthens the interconnectedness of the DSE's technological, organizational, environmental, and societal dimensions, reinforcing its role as a guiding framework for long-term sustainability transitions (Ortiz-Avram et al., 2024).

The development of DT accelerated during the COVID-19 pandemic and catalyzed widespread digital adoption, ranging from remote work solutions to AI-driven healthcare innovations (Tregua et al., 2021). However, this rapid digital expansion also underscored the dual-edged nature of technological advancements. On the one hand, cloud computing and blockchain improve supply chain transparency and promote dematerialization by reducing reliance on physical assets (Mssassi & El Kalam, 2024). On the other hand, we must address ethical concerns, digital inequalities, and cybersecurity risks to ensure technology-driven sustainability transitions (Shayganmehr et al., 2021). While cloud computing enhances resource utilization, its reliance on energy-intensive data centers underlines the need for renewable energy solutions to mitigate environmental impacts (Katal et al., 2023). Achieving this balance remains a key challenge in maximizing digital transformation's contribution to sustainability. The pandemic reinforced the necessity of embedding digital transformation within long-term sustainability strategies, ensuring its role as a catalyst for systemic change. The ability of digital technologies to support resilient and sustainable business models while adapting to external disruptions highlights their importance for future corporate and policy frameworks. To fully harness these systemic benefits, firms must integrate digital strategies with sustainability objectives at both strategic and operational levels, ensuring that technological advancements contribute to resilient, equitable, and environmentally responsible outcomes.

Digital-Sustainability Ecosystem (DSE) against the background of selected frameworks

The conceptual framework presented in this study, the Digital-Sustainability Ecosystem (DSE), provides a holistic view of how DT acts as a catalyst for SI. This section synthesizes findings from 13 frameworks identified in the literature, detailed in Table 1. We evaluate their key focus, core mechanisms, similarities, and differences with the proposed conceptual framework. This discussion evaluates the proposed framework against the identified ones, highlighting its contributions and examining its theoretical and practical implications.

Table 1. Comparative analysis of 13 frameworks and the Digital-Sustainability Ecosystem (DSE) conceptual framework in the context of digital transformation and sustainable innovation

Framework/Model	Key focus	Core mechanisms	Relation to the Digital-Sustainability Ecosystem (DSE)	Distinct contributions of the Digital-Sustainability Ecosystem (DSE)
Bag & Pretorius (2020)	Integration of Industry 4.0 technologies with sustainable manufacturing practices, particularly within the circular economy (CE) framework.	Focuses on the adoption of Industry 4.0 technologies (e.g., IoT, AI, big data analytics) to enhance resource efficiency, promote closed-loop systems, and align with CE principles.	Aligns with the Digital-Sustainability Ecosystem (DSE) pathways of efficiency gains and CE enablement by leveraging digital technologies for resource optimization and recycling.	The DSE introduces additional mechanisms of innovation acceleration through digital platforms and emphasizes multi-stakeholder digital collaboration. Moreover, the DSE integrates leadership-driven strategies and feedback loops for iterative sustainability transitions, offering a more adaptive and systemic approach.
Belhadi et al. (2022)	Integration of CE and Industry 4.0 in supply chains.	Closed-loop supply chains and dynamic capabilities.	Aligns with CE enablement and data-driven decisions.	Extends to emphasize leadership-driven digital culture, integrates collaborative innovation platforms, and incorporates systemic adaptability through feedback loops.
Calabrese et al. (2021)	Digital platform ecosystems for sustainability.	Meta-organizational models, collaboration, open innovation.	Aligns with sustainability through digital collaboration and meta-organizational principles.	Expands on multi-stakeholder engagement by integrating AI and blockchain for transparency and enhancing leadership adaptability.
Gupta et al. (2021)	Integrative framework combining Industry 4.0, cleaner production (CP), and circular economy (CE) for sustainability in manufacturing.	Multi-criteria decision-making (BWM), case study validation of Industry 4.0 practices, CE initiatives, and CP strategies.	Aligns with CE enablement, dematerialization, and efficiency gains.	Expands focus on innovation acceleration, adaptive digital leadership, and iterative feedback mechanisms, ensuring long-term sustainability.

Framework / Model	Key focus	Core mechanisms	Relation to the Digital-Sustainability Ecosystem (DSE)	Distinct contributions of the Digital-Sustainability Ecosystem (DSE)
Hallioui et al. (2022)	Systems-based management for sustainability.	Re-engineered 4th Gen. Management, stakeholder integration, Industry 4.0, and CE.	Aligns with feedback loops and stakeholder engagement.	Adds leadership-driven digital collaboration, broader technological integration (AI, blockchain), and iterative feedback mechanisms.
Li et al. (2023)	Digital Platform Ecosystems for sustainable business model innovation.	Explores the generativity, convergence, share-ability, modularity, and complementarity of digital platform ecosystems driving sustainable business model innovation.	Aligns with sustainability-oriented business models, emphasizing collaboration and customer-centric approaches through digital platforms.	Extends to incorporate dynamic interactions among pathways such as efficiency gains and digital collaboration, integrating AI-driven predictive capabilities and feedback mechanisms for continuous sustainability improvement.
Liu et al. (2022)	Digital Tech for CE.	Digital functions (e.g., monitor, track, optimize) enhance CE strategies (e.g., reuse, recycle).	Aligns with CE enablement through mechanisms like data analysis and automation.	Extends to cross-sectoral collaborations, emphasizes adaptive feedback loops, and integrates external moderators (e.g., societal and regulatory pressures).
Nascimento et al. (2019)	Integration of Industry 4.0 with circular economy (CE).	Circular Smart Production System (CSPS) using additive manufacturing (AM), CE, and reverse logistics.	Supports CE enablement through waste treatment and AM.	Extends to include multi-stakeholder collaboration, leadership-driven strategies, and feedback loops to ensure scalability and adaptability.
Samadhiya et al. (2022)	Total Productive Maintenance (TPM), Industry 4.0, and CE.	Integration of TPM, Industry 4.0, and CE for sustainability in manufacturing firms.	Aligns with process optimization and efficiency gains pathways in the DSE.	Expands on the role of adaptive digital leadership in navigating trade-offs between digital innovation and sustainability, positions CE as a critical enabler within DT processes, and enhances the integration of AI for resource optimization and sustainability-driven decision-making.
Shayganmehr et al. (2021)	Industry 4.0 and CE in ethical business.	Key enablers for CE embedded in business ethics, supported by Industry 4.0 technologies and frameworks like Fuzzy AHP and Delphi.	Supports ethical frameworks and sustainability decisions through cleaner production and CE implementation.	Integrates cross-industry digital collaboration, emphasizes the role of adaptive leadership and aligns AI-driven innovations with ethical sustainability.
Wang et al. (2023)	AI and green innovation	Explores direct, indirect, and spillover effects of AI on green innovation through industrial structure upgrades and human capital optimization..	Aligns with innovation acceleration and data-driven decisions, incorporating AI's role in CE enablement and collaborative platforms.	DSE extends by addressing AI's energy demands, embedding adaptive feedback loops, and focusing on synergies and tensions in integrating AI across systemic sustainability pathways.
Yin et al. (2023)	Digital transformation and green innovation under the Technology-Organization-Environment (TOE) framework	Examines technology, organization, and environment as interdependent factors enabling green innovation.	Supports technological, organizational, and environmental factors in digital transformation.	Adds iterative feedback mechanisms and dynamic pathways across dimensions to manage tensions and synergies; highlights leadership-driven strategies for SI.
Yuan & Pan (2023a)	Digital technology for green innovation.	Resource allocation optimization, enhanced R&D and digital infrastructure investment, and labor dynamics.	Aligns with data-driven decision-making, resource optimization, and integration of R&D with sustainability outputs.	Adds an iterative feedback loop linking digital technology applications to sustainability outputs, emphasizing adaptive learning and resilience in corporate green innovations.

Existing frameworks, such as Bag and Pretorius (2020) and Belhadi et al. (2022), emphasize Industry 4.0 and CE strategies, focusing on efficiency gains, data-driven optimization, and closed-loop supply chains. These frameworks effectively integrate dynamic capabilities to navigate sustainability transitions but overlook innovation acceleration, adaptive digital leadership, multi-stakeholder governance structures, and cross-sectoral digital collaboration mechanisms. The DSE surpasses these limitations by integrating a multi-dimensional perspective that dynamically aligns technological, organizational, environmental, and societal pathways with iterative feedback mechanisms. Unlike prior Industry 4.0-centric models, which focus on incremental efficiency improvements, the DSE framework ensures that digital transformation is deeply embedded within organizational and policy-driven sustainability transitions, promoting long-term resilience. For instance, digital platforms within the DSE facilitate AI-driven real-time collaboration, enabling open innovation ecosystems that extend beyond firm-level boundaries. This approach aligns with the diffusion of innovation and stakeholder theory while advancing beyond frameworks like Calabrese et al. (2021) and Liu et al. (2022), focusing narrowly on collaborative platforms without considering their integration with leadership inputs and iterative feedback loops. The DSE integrates AI-powered predictive capabilities, blockchain-enabled transparency, and adaptive leadership structures, ensuring that digital transformation is not merely a technological enabler but a systemic force driving cross-sectoral sustainability transformations. Similarly, Nascimento et al. (2019) explore smart production systems for CE using additive manufacturing, which aligns with the DSE's CE enablement focus. The DSE extends beyond technological advancements by embedding multi-stakeholder collaboration and leadership-driven adaptability, ensuring that sustainability transitions are scalable across industries rather than confined to specific manufacturing applications.

Moreover, frameworks like Gupta et al. (2021) and Samadhiya et al. (2022) integrate Industry 4.0 with cleaner production and circular economy models, focusing on process optimization and resource efficiency. However, these frameworks lack systemic adaptability mechanisms to accommodate evolving sustainability demands and fail to incorporate iterative learning mechanisms essential for long-term transformation. The DSE advances these contributions by embedding adaptive leadership and feedback-driven mechanisms that dynamically align blockchain, IoT, and AI technologies with sustainability imperatives. This strategic adaptability reinforces the role of leadership in resource reconfiguration and cross-industry coordination, positioning the DSE as a governance-integrated framework that bridges technological, organizational, and policy-driven sustainability efforts. Additionally, while Shayganmehr et al. (2021) address the ethical implications of Industry 4.0 and CE integration, their model lacks institutional adaptability and real-time feedback mechanisms necessary for scalable sustainability transformations. The DSE complements this perspective by incorporating adaptive leadership strategies to navigate ethical trade-offs, ensuring that AI and blockchain-driven sustainability initiatives align with global environmental and social governance (ESG) standards.

Frameworks such as Wang et al. (2023) and Yin (2023) leverage AI and the Technology-Organization-Environment (TOE) framework to explore digital innovation in green transformation. While their models effectively identify technological enablers of sustainable innovation, they treat technology adoption as an isolated driver rather than an interdependent component within broader socio-economic, regulatory, and cultural systems. In contrast, the DSE framework explicitly integrates these dimensions, acknowledging that regulatory incentives, market pressures, and stakeholder alignment are critical moderating forces in digital sustainability transitions. This distinction underscores the DSE's ability to synchronize digital strategies with evolving socio-environmental imperatives, ensuring that technological advancements translate into systemic, long-term sustainability gains.

The DSE's positioning within a continuous improvement cycle further differentiates it from existing frameworks. Unlike models that assume a linear progression of digital transformation, the DSE recognizes adaptive learning, organizational feedback, and iterative recalibration as essential for sustainability transitions. Hallioui et al. (2022) provide a comprehensive view of Industry 4.0 and CE but lack a structured mechanism for adaptive digital sustainability loops, a core principle of the DSE. Li et al. (2023) discuss the modularity and generativity of digital platform ecosystems driving sustainable business model innovation. The DSE framework focuses on digital collaboration and integrates AI-driven predictive capabilities and feedback for continuous improvement. It enhances sustainability performance through real-time monitoring and analytics, ensuring consistent refinement rather than static implementation.

Unlike Liu et al. (2022), which focuses solely on digital technology adoption, without integrating governance mechanisms, or Samadhiya et al. (2022), which emphasizes process efficiency without addressing broader systemic interdependencies, the DSE adopts a multi-dimensional perspective. The framework bridges short-term operational improvements with long-term sustainability imperatives by embedding dynamic feedback loops and external moderators. For instance, blockchain-enabled transparency and cross-sectoral collaboration within the DSE facilitate scalable circular

business models that address complex global sustainability challenges. This systemic adaptability ensures alignment with global sustainability goals, including the United Nations Sustainable Development Goals (SDGs) and regulatory frameworks such as the European Green Deal (European Commission, 2021).

Similarly, Yuan and Pan (2023a) emphasize resource allocation and digital infrastructure investment for green innovation, which aligns with the DSE's focus on optimizing resource efficiency. However, the DSE extends these principles by integrating adaptive feedback mechanisms that allow organizations to continuously refine sustainability strategies in response to evolving market and regulatory conditions. Across these comparisons, the DSE's incorporation of systemic adaptability, leadership-driven transformation, and multi-stakeholder collaboration reinforces its distinct contributions to digital sustainability discourse.

The Digital Sustainability Ecosystem (DSE) conceptual framework exemplifies an integrated approach to bridging digital transformation (DT) and sustainable innovation (SI). By synthesizing advanced digital technologies, multi-stakeholder collaboration, adaptive leadership, and iterative feedback mechanisms, the DSE provides a structured pathway for embedding sustainability into digital transformation processes. While the framework aligns with existing models in areas such as circular economy (CE) enablement, resource efficiency, and digital collaboration, it surpasses prior approaches by incorporating cross-sectoral integration and leveraging advanced technologies such as AI and blockchain to enhance transparency, adaptability, and continuous improvement.

Compared to other frameworks, the DSE emphasizes leadership-driven adaptability, dynamic feedback integration, and systemic resilience. It builds upon foundational concepts from CE and Industry 4.0 frameworks, such as those discussed by Bag and Pretorius (2020) and Gupta et al. (2021), while expanding its focus on innovation acceleration and strategic resilience. Furthermore, the DSE directly addresses tensions and synergies in the interaction between DT and SI, such as the energy demands of AI and blockchain versus their efficiency-enhancing potential and the ethical considerations of digital sustainability implementation. These refinements position the DSE as a governance-driven framework that operationalizes sustainability transitions through structured, iterative adaptation.

CONCLUSION

This study conceptualizes the Digital-Sustainability Ecosystem (DSE) framework, demonstrating how digital transformation (DT) catalyzes sustainable innovation by integrating multiple mechanisms - efficiency gains, dematerialization, circular economy enablement, innovation acceleration, and digital collaboration. When aligned with advanced technologies such as AI, IoT, blockchain, and digital platforms, these mechanisms enhance resource optimization, reduce environmental impact, and facilitate multi-stakeholder collaboration. The DSE framework introduces a systemic perspective, moving beyond isolated technological adoption to position digital transformation as an enabler of sustainability transitions, integrating technological, organizational, environmental, and societal dimensions. By synthesizing insights from existing frameworks, this study extends the theoretical discourse by illustrating how digital capabilities enable systemic sustainability outcomes through dynamic feedback loops and adaptive strategies.

The study integrates dynamic capabilities, diffusion of innovation, and the resource-based view (RBV) to highlight the strategic interplay between digital transformation and sustainable innovation. It extends the RBV by positioning digital resources as intangible assets that create sustained competitive advantages, emphasizing the role of data analytics, blockchain infrastructure, and AI-driven platforms in enhancing organizational resilience and strategic positioning. Furthermore, the study underscores the sociotechnical interplay between digital systems and human factors, demonstrating that organizational adaptability, leadership agility, and stakeholder engagement are fundamental in embedding sustainability within digital strategies. Mechanisms such as digital collaboration and innovation acceleration reinforce the importance of cross-sectoral partnerships, where governments, industries, and civil society actors co-create sustainability solutions through transparent, data-driven decision-making. The study aligns with circular economy principles by identifying digital tools as enablers of resource circularity, particularly through blockchain-enabled traceability, real-time monitoring, and AI-driven waste reduction strategies.

The DSE framework advances current literature by capturing the interdependencies between digital technologies, sustainability objectives, and institutional contexts by integrating existing theoretical approaches with sustainability-oriented concepts such as the triple bottom line, circular economy, stakeholder theory, and innovation systems. It provides a foundation for understanding the synergies and tensions within digital sustainability transitions, including AI's energy demands versus efficiency benefits or blockchain's transparency advantages versus environmental costs. These trade-offs

underscore the need for regulatory interventions that incentivize sustainable digital adoption. While policy considerations were not the central focus of this study, future research could examine how governments can shape sustainability-oriented digital ecosystems through regulatory incentives, tax benefits, and governance mechanisms.

Despite its contributions, this study has certain limitations. The conceptual nature of the DSE framework necessitates empirical validation to test its applicability across different industries, regulatory environments, and technological contexts. Additionally, the reliance on existing literature introduces potential biases inherent in secondary data, which may limit the generalizability of findings. The study also acknowledges that digital sustainability transitions are highly dynamic, requiring continuous adaptation to emerging technologies and regulatory shifts. Addressing the regulatory tensions associated with AI, blockchain, and automation remains an open area for further exploration, particularly concerning data privacy, energy consumption, and market-driven sustainability incentives.

Future research should empirically validate the DSE framework across various sectors, such as manufacturing, agriculture, and energy, to explore its scalability and sector-specific adaptability. Longitudinal studies could examine the dynamic interactions within the DSE over time, providing deeper insights into iterative feedback mechanisms and adaptive learning processes. Furthermore, exploring regional and cultural variations in digital transformation adoption would offer valuable perspectives on institutional and socio-economic barriers to sustainability-oriented digitalization. Investigating the ethical implications of digital technologies, particularly regarding data security, algorithmic bias, and the environmental trade-offs of high-energy technologies.

In conclusion, this study positions the DSE framework as a foundational model for understanding how digital transformation enables systemic sustainability transitions. By synthesizing digital capabilities, leadership adaptability, and multi-stakeholder collaboration, the framework provides a strategic pathway for organizations to align digital innovation with sustainability imperatives. The findings call for continued academic, industry, and policy engagement to maximize the potential of digital transformation in achieving resilient, transparent, and equitable sustainability outcomes.

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