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Reimagining Value by Green Business Models

The urgency of the climate crisis, supply chain disruptions and governance failures has fundamentally reshaped how organizations conceive of value creation. No longer can profitability and environmental stewardship or good governance be treated as competing priorities. Here we find a fertile ground for the enterprises to embed sustainability into the core of how they operate, generate revenue, and serve society.

The business model describes how a company achieves economic value. It refers (as per G. Hamel) to how it interfaces with customers, the key strategies used, the strategic resources, the network it is part of. Other factors to consider are the structure of the offer, the organization's position within the value chain, financial flows, logistics, how distribution is done, the moment of market entry, the use of innovative solutions, brand visibility, the pricing system, the level of customization, etc.

The green business model also refers to how it achieves ecological, social and moral values. While the term “green” naturally evokes environmental concerns, green business models encompass a far broader spectrum of value. Reducing carbon emissions and conserving resources represent only one dimension of a genuinely sustainable enterprise. Increasingly, these models integrate social and governance considerations that are inseparable from ecological goals. Social equity, fair labor practices, community engagement, and inclusive supply chains form essential pillars of the green enterprise. A business cannot claim sustainability while exploiting workers or marginalizing local communities. Likewise, transparent governance, ethical leadership, and accountability underpin the credibility of any environmental commitment. This holistic understanding aligns green business models with the broader framework of Environmental, Social and Governance criteria. True sustainability, therefore, is systemic: it balances planetary boundaries with human wellbeing and institutional integrity. Recognizing this interconnectedness allows enterprises to create durable, meaningful value that serves both present and future generations across economic, social, and ecological domains.

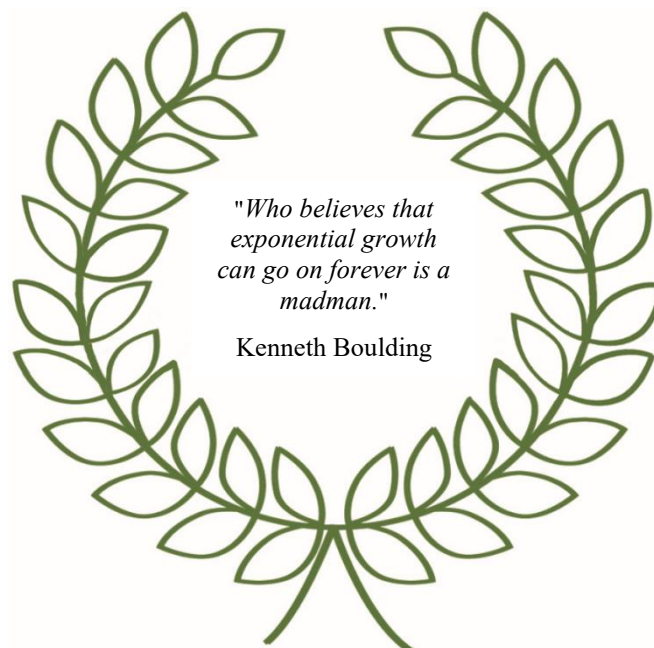


A green business model is more than a corporate social responsibility appendage or a marketing strategy dressed in sustainability language. It represents a structural transformation: a deliberate redesign of the value proposition, supply chains, resource flows, and customer relationships to minimize ecological harm while sustaining economic viability. From circular economy principles that eliminate waste through reuse and regeneration, to product-as-a-service arrangements that decouple growth from highly intensive energy or material consumption, these models challenge the linear “take-make-dispose” logic that has long dominated industry. But is not limited to that: it covers the possibilities of adapting the businesses to societal challenges or the high-speed shift of technology.

This transformation may be seen from multiple perspectives. It raises concerns about the manner firms operationalize circularity, sustainable finance, integrate renewable energy, and green innovation in reshaping competitive advantage. It also brings hope on the possibility to close resource loops to reduce costs while opening new markets or on the stakeholder’s collaboration: green business models rarely succeed in isolation. They depend on ecosystems of suppliers, regulators, consumers, and investors aligned around shared environmental goals. As such, this concept comprises the tensions and trade-offs inherent in the green transition, the risks of greenwashing, the measurement challenges of quantifying environmental impact, and the financial barriers that small and medium enterprises face when adopting sustainable practices.

We hope this issue serves this purpose, envisaging sustainability as a driver of resilience and long-term profitability rather than a constraint upon it, stimulates further research and informs practitioners navigating the complex path toward sustainable enterprise. The transition to a green economy will be shaped by the models we build today.

Beatrice LEUSTEAN
Guest Editor



Digital Communication as a Driver of Green Business Models in the Service

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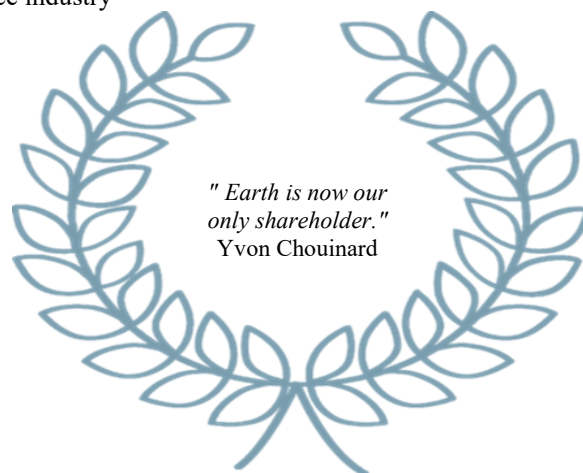
Abstract

This research was carried out to examine how digital communication can support sustainability-oriented transformation in the service industry, where value is strongly based on interaction, trust, experience, and information exchange. The paper explores the connection between digital communication and green business model development through a literature review and conceptual analysis. The results show that digital communication can strengthen green value propositions, customer engagement, transparency, circular service practices, and data-driven managerial decisions. The article proposes a framework linking digital communication mechanisms with green value creation, green value delivery, green value capture, stakeholder trust, and continuous sustainability improvement. The findings indicate that digital communication helps reduce information asymmetry, encourages customer co-creation, supports responsible consumption, and improves the credibility of environmental claims.

Keywords: digital communication, green business models, service industry

Introduction

The contemporary service industry operates in an environment shaped by two major transformation processes: digital transformation and sustainability transformation. In the view of Vial (2019), digital transformation changes how organizations use digital technologies to alter value creation processes, organizational structures, and relationships with stakeholders. In service industries, this transformation affects how companies communicate, organize activities, deliver value, interact with customers, and collect data. At the same time, sustainability changes how



companies define performance and balance economic objectives with environmental and social

responsibility. This perspective is consistent with the work of Bocken et al. (2014) and Geissdoerfer et al. (2018), who argue that sustainable business models require firms to rethink value proposition, value creation, value delivery, and value capture in relation to environmental and social outcomes.

When these two processes converge, an important managerial question emerges: how can digital communication become a driver of green business models, rather than only a promotional channel for green messages?

Previous studies have shown that sustainable business models integrate environmental and social value into the mechanisms of value creation, delivery, and capture (Bocken et al., 2014; Geissdoerfer et al. 2018). Other notable research has emphasized that digital transformation can significantly reshape business models by improving interaction, data use, innovation, and customer engagement (Vial, 2019; Rogers, 2016). At the same time, studies on green marketing and digital sustainability indicate that digital tools can increase transparency, support responsible consumption, and strengthen customer trust when environmental claims are credible and supported by real organizational practices.

The service industry is particularly relevant for this topic because services are communication-intensive by nature. As Vial (2019) and Broccardo et al. (2023) emphasize, digital transformation affects not only technological processes but also relationships, interactions, and value creation mechanisms. In hospitality, banking, education, retail, healthcare, tourism, consulting, logistics, entertainment, and public services, perceived value depends strongly on information quality, trust, responsiveness, personalization, and interaction. This is especially important in green service contexts, where, according to Geissdoerfer et al. (2018), sustainable business model innovation requires the integration of environmental value into the way organizations create and deliver value. Unlike manufacturing, where sustainability can often be assessed through physical product attributes, service sustainability is frequently intangible. Customers need to understand how a hotel reduces energy consumption, how a bank supports responsible finance, how a logistics

provider optimizes emissions, or how a tourism platform encourages low-impact travel. In this respect, OECD (2025) highlights the role of reliable environmental information in helping consumers understand and evaluate sustainability claims. These meanings are constructed and reinforced through communication.

Digital communication includes websites, mobile applications, social media, chatbots, e-mail platforms, digital dashboards, customer communities, online sustainability reports, blockchain-based traceability tools, digital labels, and platform-based interaction systems. Alkhatib et.al. (2023), associate these tools with the development of green marketing in the digital age, while Palmié et al. (2025) link digital technologies with the emergence of digital-sustainable business models. These channels can transform sustainability from a declarative corporate objective into a visible, measurable, and participatory process. For example, a hotel can communicate real-time information about water-saving practices, which is consistent with the role of green consumer engagement in hospitality discussed by Uludag et al. (2024). Similarly, a food delivery platform can show low-emission delivery options, while a bank can provide digital tools that help customers estimate the environmental impact of their consumption choices. Such examples reflect the broader argument made by OECD (2025), UNECE (2024) and UNIDO (2025) that digital solutions can support more transparent, circular, and environmentally informed consumption systems.

The aim of this study is to analyse the role of digital communication as a driver of green business models in the service industry. The specific objectives are: to clarify the relationship between digital communication, digital transformation, and green business model innovation; to identify the main mechanisms through which digital communication supports sustainability-oriented value creation in services; to propose a conceptual framework for integrating digital communication into green service business models; and to discuss managerial implications, limitations, and future research directions. The study contributes to the literature by showing that

digital communication is not only a tool for transmitting sustainability messages, but also a strategic capability that can support transparency, customer engagement, green value creation, and continuous sustainability improvement.

Literature review

Green business models. A business model describes how an organization creates, delivers, and captures value. A green business model extends this logic by integrating environmental responsibility into the core of the business, not only into peripheral corporate social responsibility activities. In this perspective, sustainability is not limited to compliance or reputation; it becomes a principle for designing offers, relationships, processes, partnerships, and revenue mechanisms.

Sustainable business model research highlights that organizations can pursue economic, environmental, and social goals simultaneously when sustainability is embedded in value proposition, value creation and delivery, and value capture (Bocken et al., 2014; Nosratabadi et al., 2019). In services, green business models may involve reducing the environmental intensity of service delivery, replacing ownership with access, encouraging reuse and repair, supporting sharing platforms, guiding responsible consumption, or using digital technologies to optimize resource allocation.

The service industry provides favourable conditions for green business model innovation because many service activities can be dematerialized or redesigned through digital tools. Online banking can reduce paper consumption and physical branch visits. Digital education can reduce commuting. Smart tourism platforms can guide visitors toward less crowded and lower-impact destinations. Telemedicine can reduce travel-related emissions. However, these benefits are not automatic. They depend on managerial choices, user behaviour, technological infrastructure, and communication quality.

Digital communication and sustainable value. Digital communication refers to the use of digital channels and technologies to transmit, exchange, personalize, verify, and co-create

information among organizations, customers, employees, partners, regulators, and communities. In green business models, digital communication has three strategic functions (Uludag et al., 2024).

First, it informs. Customers often cannot directly observe the environmental performance of a service. Digital communication can provide explanations, labels, dashboards, reports, stories, and evidence that make sustainability visible. Second, it engages. Customers are not passive recipients of sustainability messages; they can participate in recycling programmes, energy-saving behaviour, feedback communities, green loyalty schemes, and collaborative innovation. Third, it coordinates. Green business models require alignment between employees, suppliers, customers, and external stakeholders. Digital platforms can coordinate these actors by sharing data, standards, alerts, and performance indicators.

Green marketing literature emphasizes that digital media can strengthen environmental awareness and customer engagement, but only when communication is credible, transparent, and consistent with actual organizational practices (Alkhatib et al. 2023; Uludag et al., 2024). Therefore, digital communication should not be reduced to promotional content. It must be connected with operational data and managerial accountability.

Digital transformation in service organizations. Digital transformation is usually understood as a process through which digital technologies produce significant changes in organizational processes, capabilities, customer experiences, and business models (Vial, 2019). In services, digital transformation is strongly associated with customer interfaces, data analytics, automation, platforms, personalization, and ecosystem-based competition.

Digital communication is one of the most visible components of digital transformation, but it is also one of the most underestimated. Many companies invest in social media or websites without redesigning their sustainability logic. In such cases, digital communication remains superficial. A more strategic approach treats communication as an organizational capability that connects data, people, processes, and sustainability objectives.

Recent research on digital-sustainable business models suggests that digital technologies and sustainability objectives should be analysed together because digitalization can support sustainable value creation, while sustainability can guide the responsible use of digital technologies (Palmié et al., 2025). This perspective is important because digital transformation can generate both positive and negative environmental effects. Digital services may reduce paper use and travel, but they also require energy-intensive infrastructures, devices, and data centres. Therefore, green business models in services must consider both the sustainability benefits and the environmental costs of digital communication.

Grecu et al. (2025) propose a decision-oriented framework for sustainable supply chain redesign based on DEMATEL, highlighting the importance of causal relationships between sustainability factors. Although focused on supply chains, this approach is useful for service companies because green service models also require prioritization among interdependent factors such as customer communication, supplier responsibility, digital infrastructure, and environmental performance.

Grecu et al. (2025) analyse multi-attribute decision-making for intelligent allocation of human resources in industrial projects. Their approach supports the idea that digital and sustainability transformation require structured managerial decisions, not only technological adoption. In services, the same logic applies to the allocation of communication responsibilities, digital skills, green training, and customer-facing sustainability roles.

Grecu et al. (2025) examine sustainable business practices in Romania, offering a useful regional perspective on how companies integrate sustainability into managerial practice. Dinu et al. (2025) discuss interconnections of digital marketing risks through causal modelling, which is especially relevant for green communication because digital channels can amplify both trust and risk. If environmental claims are inconsistent, unclear, or exaggerated, digital communication can accelerate reputational damage.

Methodology of research

This paper is theoretical and conceptual in nature. The methodological approach involves three steps.

First, a literature review was conducted on digital transformation, digital communication, green marketing, sustainable business models, circular economy, and service management. The purpose was to identify concepts and relationships that explain how communication can influence green value creation in services.

Second, the paper applies conceptual synthesis. The literature is organized around the business model logic of value proposition, value creation and delivery, and value capture. This structure is used because it helps connect communication practices with managerial decisions and business outcomes.

Third, the paper proposes a framework called the Digital Green Communication Business Model Framework. The framework is designed for service organizations and identifies the mechanisms through which digital communication can support green business models.

The research questions are:

RQ1: How does digital communication support the development of green business models in the service industry?

RQ2: Which mechanisms connect digital communication with green value creation, green value delivery, and green value capture?

RQ3: What managerial risks and implications should service companies consider when using digital communication for sustainability transformation?

Results and discussion

Digital Green Communication Business Model Framework. Digital communication can influence green business models through five interconnected mechanisms: transparency, engagement, behavioural guidance, operational coordination, and data-based learning. These mechanisms are consistent with the broader literature on sustainable business model innovation, digital transformation,

and digital-sustainable business models, which argues that sustainability outcomes depend on the integration of value proposition, value creation,

value delivery, and value capture (Bocken et al., 2014; Vial, 2019; Geissdoerfer et al. 2018; Palmié et al., 2025) (Table 1).

Table 1 – *Digital communication mechanisms in green service business models*

Mechanism	Digital communication tools	Green business model effect	Sources
Transparency	Sustainability reports, dashboards, digital labels, traceability tools	Increases credibility and reduces information asymmetry	OECD, 2025; UNECE, 2024; Alkhatib, Kecskés and Keller, 2023; Kecskés and Keller, 2023
Engagement	Social media, apps, communities, feedback platforms	Encourages customer participation in green practices	Uludag, Ates and Aydin (2024); Alkhatib, Kecskés and Keller, 2023 , Kecskés and Keller (2023); OECD (2025)
Behavioural guidance	Eco-recommendations, nudges, personalized messages	Supports responsible consumption and low-impact choices	OECD (2025); Uludag, Ates and Aydin (2024); Alkhatib, Kecskés and Keller, 2023 , Kecskés and Keller (2023)
Operational coordination	Internal platforms, supplier portals, digital workflows	Aligns employees and partners with sustainability objectives	Broccardo et al. (2023); Vial (2019); Grecu, Dumitrescu and Niculescu, 2025a
Data-based learning	Analytics, customer data, ESG indicators, AI tools	Enables continuous improvement and adaptive green strategies	Vial (2019); Broccardo et al. (2023); Palmié et al. (2025); Dumitrescu, Grecu and Niculescu, 2025

The framework assumes that digital communication is not a single activity but a system. A service company cannot build a green business model only by publishing sustainability messages. It must integrate communication with data, operations, customer experience, and decision-making. This view is supported by studies on digital transformation, which emphasize that digital technologies create value when they reshape organizational processes, business models, and stakeholder relationships rather than functioning only as communication channels (Vial, 2019; Broccardo et al., 2023; Palmié et al., 2025).

Green value proposition. The value proposition defines what the company offers and why customers should choose it. In green service models, the value proposition includes both functional benefits and environmental benefits. Digital communication helps articulate this proposition clearly because sustainable business models require firms to connect environmental value with customer value (Bocken et al., 2014; Nosratabadi et al., 2019; Geissdoerfer et al. 2018).

For example, a hotel may offer “comfortable accommodation with reduced water and energy impact.” A bank may offer “digital financial services that support responsible investment.” A logistics provider may offer “delivery options optimized for lower emissions.” In all these cases, the environmental value must be explained in a way that is understandable, verifiable, and relevant to customers. In the hotel industry, digital marketing and green consumer engagement are especially relevant because they can influence brand loyalty and customer perceptions of sustainability (Uludag et al. 2024). In financial services, digital communication can also support customer education and risk awareness, especially where artificial intelligence and cyber resilience become part of responsible digital transformation (Dumitrescu et al., 2025).

Digital communication strengthens green value propositions by translating abstract sustainability goals into concrete customer benefits. It can show how much paper is saved by using digital invoices, how a low-carbon route is selected, or how

customer participation contributes to environmental outcomes. This translation is essential because customers rarely respond to sustainability in general terms; they respond to visible, credible, and personally meaningful information. Previous research on green marketing in the digital age shows that digital tools can improve the visibility and credibility of environmental claims when they are connected to meaningful consumer engagement and transparent information (Alkhatib et al., 2023; OECD, 2025).

Green value creation and delivery. Value creation and delivery refer to the resources, activities, partners, and channels through which the service is produced and delivered. Digital communication supports green service delivery in several ways. Sustainable business model research shows that firms need to redesign not only what they offer, but also how resources, activities, and partnerships are organized to reduce environmental impact (Bocken et al., 2014; Geissdoerfer et al., 2018; Nosratabadi et al., 2019).

First, digital communication can reduce unnecessary physical interactions. Digital booking, online consulting, remote support, e-learning, digital payments, and electronic documentation can reduce travel, paper, and waiting time. Second, it can coordinate resource-efficient operations. Internal communication platforms can inform employees about energy-saving procedures, waste reduction, or sustainable procurement rules. Third, it can support circular service practices such as repair, reuse, rental, sharing, and return systems. These practices are aligned with circular economy principles and with the use of digital tools to support circular service systems and digital servitization (Saidani et al., 2019; Koilo, 2025; UNECE, 2024; UNIDO, 2025).

In service industries, the customer is often part of the production process. A hotel guest decides whether to reuse towels. A banking customer decides whether to receive digital statements. A restaurant customer decides whether to choose plant-based or low-waste options. A passenger decides whether to select a low-emission travel route. Digital communication influences these choices by providing information at the right moment. This is important because consumer

engagement and behavioural guidance are central to the success of green service models, especially when sustainability depends on customer participation (Alkhatib et al., 2023; Uludag et al., 2024; OECD, 2025).

Green value capture. Value capture refers to how the organization obtains economic benefits from its activities. Green business models must capture value without contradicting sustainability objectives. Digital communication can support value capture through customer loyalty, premium services, lower operational costs, reputation benefits, data-driven innovation, and stakeholder trust. This is consistent with sustainable business model literature, which argues that firms must align economic value with environmental and social value (Bocken et al., 2014; Geissdoerfer et al., 2018; Nosratabadi et al., 2019).

For example, a service company may reduce costs by shifting to digital documentation, while also improving its environmental image. A tourism platform may attract environmentally conscious customers by offering transparent sustainability filters. A retailer may increase loyalty through digital repair, resale, or recycling programmes. A bank may strengthen customer retention by offering digital ESG investment education. Such examples reflect the increasing role of digital technologies in enabling sustainable business model innovation and circular economy practices (Broccardo et al., 2023; Koilo, 2025; OECD, 2025; UNIDO, 2025).

However, value capture should not be based on symbolic sustainability alone. If the company communicates green values but does not change its operations, the business model becomes vulnerable to accusations of greenwashing. Therefore, value capture must be supported by real environmental performance and transparent reporting. This is particularly important because digital platforms increase the speed and visibility of communication, making inconsistency between claims and practice more damaging for organizational credibility (Alkhatib et al., 2023; OECD, 2025).

Stakeholder trust. Trust is central in service industries because services are intangible and often evaluated through experience rather than ownership. In green services, trust becomes even

more important because customers may not be able to verify sustainability claims directly. Digital communication can reduce information asymmetry by providing evidence, explanations, and access to sustainability data (OECD, 2025; UNECE, 2024).

Digital communication can build trust by offering evidence, consistency, third-party certifications, user reviews, real-time indicators, and open feedback channels. It can also destroy trust when messages are inconsistent, exaggerated, or not supported by measurable actions. Dinu et al. (2025) show that digital marketing risks are interconnected, which means that credibility problems in one communication area can affect the entire digital relationship with customers. This supports the argument that green communication should be managed as part of a wider risk and trust framework rather than as an isolated promotional activity.

Continuous sustainability improvement

Green business models should not be static. Digital communication enables continuous

learning because it generates data about customer preferences, complaints, behaviour, and engagement. These data can help managers understand which sustainability initiatives are accepted, ignored, misunderstood, or resisted. Digital transformation research highlights that data and analytics can support organizational learning, innovation, and strategic adaptation (Vial, 2019; Broccardo et al., 2023; Palmié et al., 2025).

For example, if customers do not choose low-emission delivery, the company can analyse whether the problem is price, convenience, unclear communication, or lack of trust. If employees do not apply green procedures, internal communication data can reveal training gaps. If sustainability messages generate negative reactions, the company can revise its tone, evidence, or practices. In this sense, digital communication becomes a feedback mechanism that supports continuous improvement and more adaptive green strategies (OECD, 2025; Grecu et al., 2025a). (Table 2).

Table 2 – *Green business model components and communication tasks*

Business model component	Green objective	Digital communication task	Sources
Value proposition	Make sustainability relevant to customers	Explain environmental benefits in clear language	Bocken et al., 2014; Geissdoerfer, Vladimirova and Evans, 2018; Nosratabadi et al., 2019
Customer relationship	Build green engagement	Use interactive platforms and feedback loops	Uludag, Ates and Aydin, 2024; Alkhatib, Kecskés and Keller, 2023; OECD, 2025
Channels	Reduce physical and informational waste	Use digital self-service and paperless communication	Vial, 2019; Broccardo et al., 2023; Rogers, 2016
Key activities	Improve environmental performance	Communicate procedures, standards, and responsibilities	Bocken et al., 2014; Geissdoerfer, Vladimirova and Evans, 2018; Grecu et al., 2025
Key partners	Align the service ecosystem	Share sustainability data and supplier expectations	UNECE, 2024; UNIDO, 2025; Grecu, Dumitrescu and Niculescu, 2025
Revenue model	Capture value ethically	Link green offers with real performance, not symbolic claims	Bocken et al., 2014; Geissdoerfer, Vladimirova and Evans, 2018; OECD, 2025
Cost structure	Reduce resource intensity	Monitor savings from digitalization and green operations	Lannelongue, Grealey and Inouye, 2021; Broccardo et al., 2023; Koilo, 2025

The analysis suggests that digital communication can become a driver of green business models when it is integrated into strategy, operations, and customer experience. Several managerial implications follow.

First, managers should treat digital communication as a strategic sustainability capability. This means that communication departments, sustainability teams, IT departments, and operational managers must work together. If sustainability communication is separated from operational reality, the company risks producing attractive messages without transformational impact. This implication is aligned with the view that digital transformation requires organizational and strategic change, not only the adoption of digital tools (Vial, 2019; Rogers, 2016; Broccardo et al., 2023).

Second, service companies should prioritize transparency. Customers increasingly expect environmental claims to be supported by evidence. Digital dashboards, certificates, real-time indicators, and traceability tools can increase credibility. However, transparency must be understandable. Excessive technical information may confuse customers, while oversimplified messages may appear manipulative. Reliable environmental information is therefore essential for consumer engagement and circular economy communication (OECD, 2025; UNECE, 2024).

Third, managers should use digital communication to guide behaviour. In services, sustainability often depends on customer participation. Digital nudges, reminders, comparisons, eco-scores, and personalized recommendations can encourage responsible behaviour. Nevertheless, these tools must respect customer autonomy and privacy. This balance is important because digital green marketing can strengthen engagement, but it can also create risks when communication becomes intrusive, unclear, or misleading (Alkhatib, Kecskés and Keller, 2023; Dinu et al., 2025; Uludag, Ates and Aydin, 2024).

Fourth, service firms should develop green digital skills. Employees need to understand both digital tools and sustainability objectives. A chatbot, for example, cannot support a green business model if its answers are generic or

disconnected from real sustainability practices. Frontline employees must also be able to explain green service options and respond to customer concerns. The need for such capabilities is consistent with research on digital-sustainable business models, which emphasizes the integration of technology, strategy, people, and sustainability objectives (Palmié et al., 2025; Broccardo et al., 2023).

Fifth, companies must manage the risks of greenwashing. Digital platforms amplify visibility. A misleading claim can spread quickly and damage reputation. Therefore, environmental messages should be checked against actual data, legal requirements, and stakeholder expectations. The work of Grecu and co-authors on decision frameworks and digital marketing risks is relevant here because it emphasizes the importance of structured analysis and causal thinking in complex managerial contexts (Dinu et al., 2025; Grecu et al., 2025a; Grecu et al., 2025).

Sixth, managers should consider the environmental footprint of digital communication itself. Digitalization is often presented as automatically green, but data storage, cloud services, devices, and AI tools consume energy. A green service model should therefore include responsible digital infrastructure choices, efficient data management, and awareness of digital carbon impacts. This is supported by research on the carbon footprint of computation and by recent discussions on the relationship between digitalization and circular economy transitions (Lannelongue, Grealey and Inouye, 2021; UNECE, 2024; UNIDO, 2025).

Conclusion

Digital communication is a major driver of green business models in the service industry because it connects sustainability strategy with customer experience, operational coordination, stakeholder trust, and continuous learning. In services, where value is intangible and co-created through interaction, communication determines whether sustainability is understood, trusted, and adopted.

The paper shows that digital communication supports green business models through transparency, engagement, behavioural guidance, operational coordination, and data-based learning. These mechanisms influence green value proposition, green value creation and delivery, and green value capture. However, the impact of digital communication depends on managerial integrity and operational alignment. Communication cannot replace real sustainability performance; it can only make it visible, understandable, and actionable.

The proposed Digital Green Communication Business Model Framework offers a conceptual tool for managers and researchers. It can help service companies evaluate whether their digital communication practices are merely promotional

or genuinely transformative. Further studies could test the framework empirically in specific service sectors such as hospitality, banking, tourism, education, healthcare, logistics, or retail. Future research could also examine customer responses to green digital communication, the role of artificial intelligence in sustainable service personalization, and the balance between digital efficiency and digital environmental footprint.

Digital communication is not only about sending messages. In green service business models, it becomes a managerial infrastructure for building trust, changing behaviour, coordinating stakeholders, and transforming sustainability into everyday service value.

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The Application of Artificial Neural Networks for Pollution Detection in Danube River

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Abstract

This study explores the application of Artificial Neural Networks (ANN) to enhance pollution detection and water quality forecasting in the Romanian Danube basin, leveraging standardized data from the International Commission for the Protection of the Danube River (ICPDR). Various ANN architectures, including feedforward networks, LSTM, and wavelet-ANN hybrids, are examined for their ability to model nonlinear environmental relationships. The research integrates ICPDR's TransNational Monitoring Network (TNMN) and Joint Danube Surveys (JDS) datasets, demonstrating high predictive accuracy ($R^2 > 0.9$ in many cases) for parameters such as dissolved oxygen, water quality index, and temperature as a pollution proxy. This positions Romania to lead in green AI entrepreneurship while advancing sustainable Danube management.

Keywords: Artificial Neural Networks, water quality forecasting, wavelet-ANN hybrids

Introduction

The Danube River, Europe's second-longest waterway, crosses 19 countries and supports critical ecosystems, agriculture, industry, and communities. In Romania, the lower Danube and UNESCO-listed Danube Delta Biosphere Reserve face cumulative transboundary pollution from upstream nutrient loads, heavy metals, and emerging contaminants. Traditional monitoring struggles with the nonlinear, dynamic nature of these pressures (Antanasijević et al., 2013).

ANN, as a subset of AI, excel at capturing complex multivariate patterns and forecasting in noisy environmental datasets. This paper investigates ANN applications for pollution detection in the Romanian Danube, utilizing



harmonized ICPDR data. It also demonstrates how such research can fuel entrepreneurial initiatives in

green AI, aligning with Romania's National AI Strategy 2024–2027 and the RO AI Factory initiative (RO AI Factory Consortium, 2025).

Research methodology

This study employs a systematic literature review (SLR) combined with a comparative analysis and entrepreneurial opportunity mapping to evaluate the application of Artificial Neural Networks (ANN) for pollution detection and water quality forecasting in the Romanian segment of the Danube River. The methodology follows the PRISMA guidelines for systematic reviews where applicable and integrates a business-oriented perspective using the Business Model Canvas framework.

A systematic search was conducted across major academic databases (ScienceDirect, SpringerLink, MDPI, IEEE Xplore, Google Scholar) and official ICPDR repositories between October 2025 and February 2026. The search combined keywords such as “Artificial Neural Networks Danube”, “ANN water quality”, “LSTM pollution forecasting Danube”, “wavelet-ANN”, “WQI prediction Danube”. The inclusion criteria required that studies: (1) be peer-reviewed publications published between 2013 and 2025, (2) focus on the Danube River Basin or similar transboundary river systems, (3) explicitly apply ANN architectures such as Multi-Layer Perceptron (MLP), Long Short-Term Memory (LSTM), Generalized Regression Neural Network (GRNN), or wavelet-ANN hybrid models for predicting water quality parameters including dissolved oxygen (DO), biological oxygen demand (BOD), nutrients, Water Quality Index (WQI), temperature, and heavy metals; and (4) provide quantitative performance metrics such as the coefficient of determination (R^2), root mean square error (RMSE), mean absolute error (MAE), mean squared error (MSE), or clear validation results. Through this process, after removing duplicates and screening, 28 relevant studies were selected, with strong representation from Romania (four studies), Serbia (eight studies), Hungary (three studies), and several cross-basin comparative analyses. Grey literature such as ICPDR TNMN Yearbooks and

Joint Danube Surveys (JDS) reports was also utilized for contextual data (European Commission, 2000/ongoing; Šiljić Tomić et al., 2016).

The study draws on harmonized, publicly available ICPDR datasets, including the TNMN Yearbooks, which provide annual physico-chemical, biological, and hydrological parameters from approximately 101 monitoring stations (Šiljić Tomić, et al., 2016). It also incorporates data from the Joint Danube Surveys (JDS3 in 2013, JDS4 in 2019), and the ongoing JDS5 scheduled for 2025–2026), offering high-resolution, basin-wide snapshots that include emerging techniques such as environmental DNA (eDNA) and microplastics analysis (European Commission, 2000/ongoing). In addition, National Romanian monitoring data from Romanian Waters stations, such as those at Chiciu–Calarași, are included, along with complementary satellite products like Sentinel-2 multispectral bands used as proxies for turbidity and chlorophyll-a concentrations. No new primary data collection was conducted for this study; rather, the analysis synthesizes existing validated datasets that have been utilized in the reviewed ANN research.

ANN Models and Architectures Evaluated

The assessment covered several ANN architectures and hybrid models based on their documented applications in the Danube River or similar river systems. Feedforward Multilayer Perceptron (MLP) networks with Levenberg-Marquardt backpropagation were commonly used for static regression tasks such as temperature forecasting. Cascade-Forward Networks (CFN) and Radial Basis Function (RBF) networks were applied to WQI prediction and nonlinear pattern recognition tasks. Long Short-Term Memory (LSTM) networks were employed for time-series forecasting of pollution indicators including dissolved oxygen DO, nutrients, and BOD. Generalized Regression Neural Network (GRNN) were utilized in Serbian studies to forecast DO, BOD, and nitrate concentrations along extended river sections. Additionally, Wavelet-ANN hybrids, which

combine decomposition techniques such as Discrete Wavelet Transform (DWT) with ANN models like Backpropagation Neural Networks (BPNN), Nonlinear Autoregressive with Exogenous input (NARX), or LSTM, as well as true wavelet neural networks using wavelet activation functions like Morlet, were evaluated for their capacity to handle non-stationary data series. These hybrid models were informed by analogous applications in rivers such as the Elbe and considered for potential transferability to the Danube context.

Model inputs typically included physico-chemical parameters such as temperature, pH, dissolved oxygen, nitrates, phosphates, BOD, chemical oxygen demand (COD), and turbidity. Hydrological variables like flow rate, water level, and lagged values were also incorporated, with some models integrating biological indicators including chlorophyll-a concentrations and macroinvertebrate data. Model outputs generally focused on pollutant concentrations, WQI scores, or categorical risk classifications.

To systematically address these computational challenges, the selection of an appropriate network paradigm must align with the specific temporal, spatial, and stochastic characteristics of the target water quality parameters. The architectural continuum evaluated in this study ranges from static baseline models to highly specialized hybrid configurations. Conventional Feedforward MLPs serve as a robust baseline for stationary or localized

regressions, such as predicting water temperature gradients or localized dissolved oxygen dynamics. However, when environmental monitoring requires capturing complex, non-linear seasonal transitions, Cascade-Forward and RBF networks offer enhanced performance due to their localized activation properties. For continuous time-series modeling where capturing hydrochemical memory is critical, LSTM networks excel at identifying delayed upstream transport impacts and sudden pollution spikes, as demonstrated in recent national pilots. Conversely, large-scale spatial modeling over extensive river stretches shifts the computational preference toward GRNNs. This probabilistic framework is highly favored in extensive regional studies along the Serbian Danube basin (Antanasijević et al., 2013; Krtolica et al., 2021; Mitrović et al., 2019; Šiljić Tomić et al., 2016) due to its rapid single-pass learning convergence and high accuracy when dealing with geographically distributed metrics. Finally, for highly volatile, non-stationary parameters influenced by seasonal flooding or complex runoff behaviors—such as toxic heavy metal concentrations—Wavelet-ANN (WANN) hybrids provide the necessary multi-scale resolution by decomposing noisy raw data before network execution. A systematic synthesis of these evaluated architectures, including their input-output configurations and localized strengths, is presented in Table 1.

Table 1 - Summary of ANN Architectures Evaluated in the Study

Architecture	Key Characteristics	Typical Inputs (Examples)	Typical Outputs	Strengths in Danube Context	Representative Studies (Danube or Analogous)
Feedforward MLP	Simple layered structure, backpropagation	Temperature, pH, flow, lagged values	Temperature, concentration, WQI	Fast training, good for static regression	Ionescu (2025) – temperature forecasting
Cascade-Forward / RBF	Enhanced connectivity, radial basis functions	Physico-chemical+ hydrological parameters	Water Quality Index (WQI)	Strong nonlinear modeling, seasonal performance	Georgescu et al. (2023)–WQI forecasting
LSTM	Memory cells for long-term dependencies	Time-series sequences (DO, nutrients, lagged data)	Time-series forecasts (DO, BOD, nutrients)	Captures long dependencies, pollution spikes	Emerging Romanian Delta pilots

GRNN	Probabilistic, fast convergence	Physico-chemical, flow over long stretches	DO, BOD, nitrates	High accuracy on large spatial domains	Serbian studies (Antanasijević et al., 2014)
Wavelet-ANN Hybrids (WANN)	DWT decomposition + ANN modeling	Non-stationary series (heavy metals, runoff)	Long-term pollutant concentrations	Handles non-stationarity, noise reduction, multi-scale	Li et al. (2020) – Elbe heavy metals (analogous)

(Source: Adapted from Antanasijević et al. (2013), Csábrágyi et al. (2017), Georgescu et al. (2023), Ionescu et al. (2025), Krtolica et al. (2021), Li et al. (2020), Mitrović et al. (2019). Šiljić Tomić et al. (2016)).

Comparative performance of the models was assessed using standard metrics commonly reported in the literature. These included the R^2 , which measures the proportion of variance explained by the model; RMSE and MAE, which quantify the absolute prediction errors; and MSE, primarily used for regression tasks. Validation approaches across studies involved techniques such as train/test data splits, k-fold cross-validation, and out-of-sample testing using recent data periods. Where available, hybrid models - particularly wavelet-ANN hybrids - were benchmarked against standalone ANN models to evaluate relative performance improvements.

To translate technical findings into business potential, the study aligned ANN prototypes with Romania's AI entrepreneurship ecosystem. This included initiatives such as RO AI Factory, launched in October 2025, which provides supercomputing resources and support for scaling AI models (RO AI Factory Consortium, 2025). The UPBizz Centre and Innovation Labs at POLITEHNICA University of Bucharest offer pre-acceleration programs and spin-off support for AI startups. The Interreg BrAIIn project (2024–2026) promotes AI adoption among small and medium-sized enterprises (SMEs) in water-related sectors (Interreg Danube Programme, 2024–2026). Additionally, various European Union funding instruments, including Horizon Europe Cluster 6 and Danube Lighthouse Actions such as DaWetRest and Restore4Life, facilitate pathways for advancing prototypes to market-ready solutions (European Commission, 2021–2027; ICPDR / EU Danube Strategy, 2021–ongoing). Business model elements—including software-as-a-service (SaaS) platforms, consulting services, and data-as-a-

service offerings—were structured using the Business Model Canvas framework, emphasizing value propositions, revenue streams, and customer segments relevant to stakeholders along the Danube. This comprehensive approach ensures a balanced evaluation of ANN technical capabilities alongside their potential to foster green AI entrepreneurship in Romania, grounded in ICPDR data and practical applications within the Danube basin.

Results and discussion

ANN Performance in the Romanian Danube.

Recent Romanian studies (2023–2025) demonstrate that ANN models achieve high predictive accuracy for water quality parameters in the lower Danube and Danube Delta region.

Ionescu (2025) developed a feedforward ANN model using Levenberg-Marquardt backpropagation to forecast seven-day water temperature at the Chiciu – Calarași monitoring station, located near the Romanian-Bulgarian border. The model incorporated inputs such as air temperature, lagged water temperature, and river discharge, achieving root mean square error (RMSE) values ranging from 0.803 to 0.954 °C on the test dataset. This level of accuracy positions temperature forecasting as a reliable indirect proxy for assessing thermal stress and dissolved oxygen (DO) dynamics, which are critical near ecologically sensitive areas like the UNESCO-designated Danube Delta Biosphere Reserve and industrial sites such as the Cernavoda Nuclear Power Plant, where stable thermal conditions are essential for cooling water intake. Temperature plays a significant role in influencing DO solubility, microbial activity, and chemical

reaction rates, linking the model's output to broader pollution monitoring and ecological risk assessments (Georgescu et al., 2023).

In the study, Georgescu et al. (2023) applied CFN and RBF networks to forecast the WQI using physical-chemical and hydrological parameters collected from Romanian monitoring stations integrated with ICPDR's TNMN data. The CFN models outperformed the RBF networks, with MSE values between 0.083 and 0.319 and correlation coefficients (R) approximately ranging from 0.91 to

0.94. These models effectively captured nonlinear relationships and seasonal variations in water quality, demonstrating stronger predictive performance during colder periods. The findings underscore the capability of ANNs to provide robust short-term forecasts of WQI, which supports early warning systems for nutrient enrichment, organic pollution, and hazardous substance exceedances in the lower Danube segment where cumulative pollution loads from upstream converge (ICPDR, various years). (Table 2).

Table 2 - Performance Summary of Key Romanian ANN Studies

Study	Model Type	Key Parameter (s)	Performance Metrics	Location / Focus	Main Implications
Ionescu (2025)	Feedforward ANN (Levenberg-Marquardt)	Water temperature (7-day forecast)	RMSE: 0.803–0.954 °C	Chicluș-Călărași station	Indirect proxy for DO/thermal stress; Delta & NPP relevance [5]
Georgescu et al. (2023)	Cascade-Forward (CFN) & RBF	Water Quality Index (WQI)	MSE: 0.083–0.319; R ≈ 0.91–0.94	Romanian Danube monitoring stations	Strong nonlinear/seasonal forecasting; early warning potential [6]

(Source: Adapted from Georgescu et al. (2023) and ICPDR (various years)).

Both studies confirm that ANN models trained on harmonized ICPDR TNMN and national Romanian datasets consistently achieve R^2 greater than 0.90 and maintain low error metrics on validation datasets. This performance demonstrates the practical potential of ANN methodologies for proactive pollution management in Romania's ecologically sensitive downstream regions of the

Danube River (European Commission, 2000/ongoing and Šiljić Tomić et al., 2016).

Basin-wide Comparison. Across the ICPDR basin, applications of ANN remain largely at the research and pilot stages, with no large-scale operational systems deployed as of February 2026. The performance and scope of these applications vary significantly among countries. (Table 3).

Table 3 - Comparative Overview of ANN Applications Across ICPDR Countries

Country	Leading Architectures	Key Parameters / Innovations	Best Reported Performance	Strengths / Focus	Maturity Level (as of 2026)
Romania	Feedforward MLP, CFN, RBF, emerging LSTM	Temperature, WQI	RMSE 0.803–0.954 °C; R ≈ 0.91–0.94	Downstream proxies, Delta relevance, rapid recent progress	Most developed (multiple publications)
Germany/Austria	Limited published surface ANN; more groundwater/hydrology ML	Groundwater levels, flow	High in hydrology tasks	Traditional modeling dominance, high-density monitoring	Strong but more limited scope

Serbia	GRNN, Monte Carlo-optimized multi-target ANN	DO, BOD, nitrates, virtual monitoring at inactive sites	R^2 up to ~ 0.97 ; MAPE $< 10\%$	Broadest parameters, spatial interpolation, uncertainty handling	Advancing rapidly, focused on forecasting proxies
Hungary	Multilayer feedforward ANN	Dissolved oxygen (DO)	$R^2 > 0.9$	Foundational DO forecasting, nonlinear modeling	Lower emphasis on published surface pollution ANN

(Source: Adapted from Antanasijević et al. (2013), Csábrági et al. (2017), Georgescu et al.

(2023), ICPDR (various years); ICPDR (2013, 2019, 2025–2026); Ionescu et al. (2025), Krtolica et al. (2021), Mitrović et al. (2019); Šiljić Tomić et al. (2016)).

Serbia is a leader in direct pollution-parameter forecasting and practical innovation. Studies there have applied GRNN to predict DO, BOD, and nitrate concentrations (ICPDR, 2013, 2019, 2025–2026; Krtolica et al., 2021; Li et al., 2020; Mitrović et al., 2019) along extensive river stretches of up to 588 kilometres, achieving R^2 as high as approximately 0.97. Mitrović et al. (2019) introduced Monte Carlo-optimized multi-target ANNs for virtual monitoring at inactive stations, successfully interpolating 18 parameters including pH, nutrients, DO, BOD, and heavy metals, with mean absolute percentage errors below 10% in many cases. Additional Serbian research includes BOD modelling with spatial-temporal optimization (Tomić et al., 2016) and ecological status prediction based on macrophyte data using ANN (Krtolica et al., 2021), which utilized data from the JDS3. Serbia's strengths lie in its broad parameter coverage, innovations in virtual station monitoring, and sophisticated approaches to managing uncertainty.

Hungary has made foundational contributions, particularly in forecasting dissolved oxygen (RO AI Factory Consortium, 2025). Csábrági et al. (2017) employed a multilayer feedforward ANN on the Hungarian section of the Danube, integrating inputs such as pH, temperature, and flow, achieving R^2 values greater than 0.9 in modelling oxygen depletion. Although this early work has influenced subsequent studies in the middle and lower basin, Hungary's applications remain more limited in scope compared to Serbia.

In the upper basin, Germany and Austria focus primarily on traditional hydrodynamic and physically based modelling approaches, supported by dense national monitoring networks such as Germany's LAWA. Integration of ANN and machine learning techniques appears more common in groundwater and hydrology applications or as internal tools, with fewer published peer-reviewed studies specifically addressing surface-water pollution forecasting for the Danube main stem compared to countries in the middle and lower basin.

Romania is advancing rapidly in forecasting proxy variables such as temperature and WQI, as well as applications relevant to the Danube Delta. However, it currently lags behind Serbia in terms of publication volume, diversity of monitored parameters, and innovative features like virtual monitoring stations (Georgescu et al., 2023; ICPDR, various years). Across the entire basin, the maturity of ANN applications reflects research focus rather than operational deployment: Serbia and Hungary lead in direct pollution forecasting, while Romania is making significant progress in downstream-specific proxies with promising integration potential from emerging data sources such as those expected from the upcoming Joint Danube Survey 5 (JDS5), which includes novel indicators like environmental DNA (eDNA) and microplastics (European Commission, 2000/ongoing).

Entrepreneurial translation

The high performance of ANN prototypes directly translates into commercial opportunities within Romania's expanding green AI ecosystem. Predictive software-as-a-service (SaaS) platforms, utilizing models such as LSTM or wavelet-ANN hybrids, have the capability to provide real-time dashboards, short-term pollution forecasts ranging from one to seven days, and automated alerts tailored for water utilities, agricultural cooperatives, fisheries, and energy producers. These services address critical needs related to regulatory compliance, risk mitigation, and operational efficiency. Additionally, consulting and integration services offer the potential for customized ANN deployments and explainable AI solutions that can be extended to other ICPDR member countries and nations within the Black Sea basin.

Delta-focused climate technology ventures are emerging, combining IoT, satellite data, GIS, and ANN systems to monitor biodiversity-sensitive zones. Such digital twin and 3D visualization platforms can serve as a "digital foundation" for integrating live sensor and satellite data into interactive operational dashboards. These commercial pathways align with national support structures such as the RO AI Factory, launched in October 2025, which provides supercomputing resources for model scaling (Csábrági et al., 2017); the UPBiz Centre and Innovation Labs, which offer pre-acceleration and spin-off support; and the Interreg BrAIIn project (2024–2026), which promotes AI adoption among SMEs in water-dependent sectors including agro-food, manufacturing, and green energy (Interreg Danube Programme, 2024–2026). European Union funding mechanisms, including Horizon Europe Cluster 6 and Danube Lighthouse Actions such as DaWetRest and Restore4Life, further facilitate the transition from prototypes to market-ready solutions (Ionescu et al., 2025).

By leveraging ICPDR data (European Commission, 2000/ongoing; Šiljić Tomić et al., 2016) alongside academic expertise, these ANN-based models are poised to generate high-skilled employment, exportable technologies, and sustainable revenue streams within 12 to 18 months.

This positions Romania as a regional leader in AI-supported river management and green technology entrepreneurship. Collectively, the results highlight the dual value of ANNs: they provide scientifically robust tools for pollution forecasting that enhance transboundary water protection, while also fostering commercially viable innovations that strengthen economic and environmental resilience in Romania's downstream Danube context.

Conclusions

This study demonstrates that Artificial Neural Networks (ANN) provide a robust predictive framework for pollution detection and water quality forecasting in the Romanian Danube basin. ANN architectures, particularly LSTM and wavelet-ANN hybrids, effectively model complex nonlinear relationships and outperform traditional methods when trained on harmonized ICPDR data. Empirical evidence from recent Romanian research confirms high accuracy ($R^2 > 0.90$) for key parameters such as water temperature and Water Quality Index.

The findings highlight Romania's strategic position as the downstream recipient of transboundary pollution. Advanced ANN applications can significantly support the protection of the Danube Delta Biosphere Reserve, fisheries, eco-tourism, and critical infrastructure, while contributing to EU Water Framework Directive objectives. Basin-wide comparisons reveal that although Serbia leads in direct pollution forecasting, Romania is advancing rapidly in proxy variables and Delta-specific solutions.

Beyond technical contributions, this research provides an entrepreneurship roadmap. ANN prototypes can be developed into scalable green AI solutions - including SaaS platforms, real-time forecasting services, and digital twin applications - aligned with Romania's National AI Strategy 2024–2027 and the RO AI Factory initiative. Supported by EU funding mechanisms and national accelerators, these innovations have strong potential to generate high-skilled employment, exportable technologies, and measurable reductions in pollution-related economic losses.

Future progress will require sustained investment in data infrastructure, cross-border

collaboration, and the integration of emerging data sources such as JDS5 (eDNA, microplastics). If realized, the Danube Basin could become a European model for AI-supported transboundary

river management, with Romania playing a leading role in sustainable water innovation and green-tech entrepreneurship.

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Artificial Intelligence as Driven in the Transition Toward Green Business Models

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Abstract

This study examines how artificial intelligence supports organizational resilience during this transition. Following PRISMA 2020, a systematic literature review of 20 articles published between 2023 and 2026 and indexed in the Web of Science Core Collection was conducted using thematic synthesis. The findings indicate that AI strengthens resilience through predictive analytics, intelligent decision support, process optimization, organizational learning, and adaptive capabilities. These mechanisms support circular practices, green innovation, sustainable supply chains, low-carbon operations, and business model transformation. Their effectiveness depends on organizational readiness, data quality, human oversight, governance, and technological infrastructure. The study develops an integrated thematic framework linking AI capabilities, organizational resilience, and green business model transformation.

Keywords: artificial intelligence, green business models, sustainable transformation

Introduction

Organizations increasingly operate under conditions shaped by rapid technological change, environmental pressure, supply-chain disruption, and rising stakeholder expectations. In this context, the transition toward green business models has become an important strategic objective for firms seeking to combine economic performance with reduced environmental impact and sustainable value creation.

This transition requires more than isolated environmental practices or efficiency measures. Organizations must be able to anticipate risks, maintain essential activities during disruptions, adapt their processes, and reconfigure resources in



response to changing conditions. These capabilities are closely associated with organizational resilience, understood as the capacity to prepare for, respond to, recover from, and learn from disruptive events while preserving or transforming core organizational functions.

Artificial intelligence can strengthen organizational resilience through predictive analytics, real-time monitoring, intelligent decision support, process optimization, automation, and organizational learning. These technologies can help firms identify operational and environmental risks, improve resource allocation, reduce waste, increase supply-chain visibility, and respond more rapidly to unexpected events. They may also support the redesign of products, processes, partnerships, and value networks required for greener forms of business activity.

However, AI adoption does not automatically generate sustainable outcomes or green business model transformation. Its contribution depends on data quality, organizational readiness, workforce capabilities, human oversight, governance arrangements, and the alignment of technological applications with environmental and strategic objectives. Firms may become more efficient or resilient without fundamentally changing how they create, deliver, and capture value.

Existing studies often examine artificial intelligence, organizational resilience, and sustainability as separate research areas. Although recent literature connects AI with sustainable operations, circular practices, green innovation, and resilient supply chains, the pathway through which AI-enabled resilience capabilities support green business model transformation remains insufficiently integrated. This paper addresses that gap by examining how AI strengthens anticipation, absorption and recovery, adaptation and reconfiguration, and strategic transformation, and how these capabilities support circularity, green innovation, sustainable supply chains, low-carbon operations, and business model redesign. Based on systematic review, the study develops an integrated thematic framework connecting AI capabilities, organizational resilience, and green business model transformation.

Literature review

Organizational resilience has evolved from a reactive concept focused on recovery after disruption into a broader organizational capability involving anticipation, adaptation, learning, and transformation. Early and recent contributions describe resilience as the ability to maintain essential functions, develop alternative configurations, and, in more advanced forms, transform organizational objectives, structures, and practices in response to adversity (Lengnick-Hall et al., 2011; Linnenluecke, 2017; Hillmann and Guenther, 2021; Hepfer and Lawrence, 2022).

Recent studies suggest that artificial intelligence can strengthen these resilience capabilities when it is embedded in organizational processes rather than used as an isolated technical tool. AI assimilation has been linked to sustainable performance, organizational agility, green innovation, supply-chain resilience, and corporate green resilience (Zhang and Dong, 2026; Chowdhury et al., 2026; Xin et al., 2026). AI-supported planning may also improve operational resilience under carbon constraints, especially when organizations face supply-chain disruptions or environmental performance requirements (Kaur et al., 2026).

The organizational impact of AI depends not only on technology, but also on managerial, human, and knowledge-related capabilities. Studies show that AI contributes to eco-innovation, green innovation, circular-economy adoption, and sustainable performance when firms possess organizational agility, technological readiness, knowledge-integration capacity, and green learning capabilities (Ahmed et al., 2026; Ashergawi et al., 2026; Alzeiby et al., 2026; Huang and Zhao, 2026; Zahoor et al., 2025). These findings indicate that AI-enabled resilience is shaped by the interaction between digital capabilities and organizational readiness.

A more direct research stream examines the role of AI in green and sustainable business model innovation. AI capabilities have been associated with circular business model innovation, sustainable business model innovation, resource reconfiguration, sustainable competitive advantage,

and digitally enabled business models (Sjödén et al., 2023; Wang et al., 2025; Anh et al., 2026; Sangnak, 2026; Islam et al., 2025; Sanchez et al., 2025). Other studies show that managerial and technical AI knowledge, AI-enabled analytics, digital twins, cognitive automation, and resource optimization can support circularity, sustainable value chains, resilient supply chains, and regenerative innovation ecosystems (Al Halbusi et al., 2025; Mehmood et al., 2026; Aldhaheri et al., 2025; Fernández-Miguel et al., 2025; Capatina et al., 2026).

Taken together, the literature indicates that AI contributes to green transformation through several interconnected mechanisms, including prediction, environmental sensing, intelligent decision support, organizational learning, agility, resource reconfiguration, and business model redesign. However, improved operational efficiency or resilience does not automatically produce a green business model. Many AI applications improve forecasting, continuity, resource efficiency, emissions management, or circular operations without changing the organization's value proposition, value-delivery architecture, or value-capture mechanisms.

The reviewed literature therefore reveals an important distinction between AI-enabled operational improvement and AI-enabled green business model transformation. The first concerns efficiency, continuity, and environmental performance improvements, while the second involves more substantial changes in business design, partnerships, organizational capabilities, and sustainable value creation. Although existing studies provide evidence for both levels, the complete pathway linking AI capabilities, organizational resilience, and green business model transformation remains fragmented.

Research methodology

This study applies a focused systematic literature review to examine how artificial intelligence contributes to organizational resilience in the

transition toward green business models. The review follows the PRISMA 2020 framework (Page et al., 2021) and uses thematic synthesis to identify AI mechanisms, resilience capabilities, green transformation outcomes, enabling conditions, and implementation barriers.

Scientific publications were identified through a structured search conducted in the Web of Science Core Collection on June 30, 2026. Web of Science was selected as the sole database to ensure consistency in metadata, document classification, and record processing. The search strategy combined three groups of terms related to artificial intelligence, organizational resilience, and green or sustainable business transformation. The final search query was:

TS=((("artificial intelligence" OR "machine learning" OR "deep learning" OR "predictive analytics" OR "AI-enabled" OR "AI-driven" OR "digital twin*") AND ((resilien* NEAR/3 (organization* OR business* OR enterprise* OR firm* OR operation* OR strateg*)) OR ((dynamic capabilit*" OR adaptab* OR agilit* OR "business continuity" OR "operational continuity") NEAR/5 (organization* OR business* OR enterprise* OR firm*))) AND ((("business model*" NEAR/5 (green OR sustainab* OR circular*)) OR "green transition" OR "sustainable transition" OR "green transformation" OR "sustainable transformation" OR "green innovation" OR "circular econom*" OR decarbonization OR "low-carbon" OR "resource efficiency" OR "sustainable supply chain*")))

The search identified 145 records published between 2020 and 2026. After restricting the dataset to articles and review articles, applying the English-language filter, removing one duplicate, and completing title, abstract, and full-text screening, the final corpus consisted of 20 studies. These included 11 studies with direct business-model relevance and nine studies providing strong evidence of an enabling pathway toward green

transformation. The complete selection process is presented in the PRISMA flow diagram.

Studies were included when artificial intelligence represented a central explanatory capability, intervention, or organizational resource rather than an incidental concept or analytical technique. They also had to examine an explicit organizational resilience mechanism, such as resilience, agility, adaptability, dynamic capabilities, continuity, recovery, organizational learning, or strategic reconfiguration. A further requirement was green business model relevance, either through direct reference to sustainable or circular business models, business model innovation, sustainable value creation, delivery or capture, or through a clear strategic pathway from AI-enabled organizational capabilities toward green transformation.

Studies were excluded when AI was mentioned only marginally, used only as a statistical or technical tool, or combined with broader digital technologies in a way that prevented the AI-specific contribution from being identified. Research focused only on technical systems, infrastructure, emissions reduction, environmental optimization, or operational efficiency was also excluded when it did not provide evidence of organizational resilience or business-model transformation. The final inclusion decision required evidence supporting the integrated pathway: AI capability → organizational resilience or adaptation → green business model transformation.

A structured data-extraction matrix was developed for the final corpus. For each study, the analysis recorded the authors, publication year, journal, document type, sectoral context, AI technology or capability, organizational resilience mechanism, green transformation outcome, business-model relevance, and main findings.

The thematic synthesis was conducted in three stages. First, the studies were coded according to the

principal functions performed by AI, including prediction, forecasting, real-time monitoring, intelligent decision support, process optimization, automation, simulation, knowledge integration, and organizational learning. Second, these mechanisms were grouped into four resilience capabilities: anticipation, absorption and recovery, adaptation and reconfiguration, and strategic transformation. Third, the resilience capabilities were connected to green transformation outcomes, including circularity, resource efficiency, sustainable supply chains, low-carbon operations, green innovation, regenerative value creation, and sustainable business model redesign.

Multiple coding was permitted because a single study could address more than one AI mechanism, resilience capability, or green outcome. Strategic transformation was coded when a study described substantial organizational or strategic change, while direct green business model transformation required explicit evidence concerning business design, value creation, value delivery, or value capture. The resulting themes were used to develop an integrated thematic framework linking AI capabilities, organizational resilience, and green business model transformation.

Results and Discussion

Study Selection and Corpus Profile. The systematic search in the Web of Science Core Collection (Figure 1) identified 145 records published between 2020 and 2026. After applying document-type and language filters, removing one duplicate, and completing title, abstract, and full-text screening, the final focused corpus consisted of 20 studies. Of these, 11 studies had direct business-model relevance, while nine provided strong enabling evidence for the pathway linking AI capabilities, organizational resilience, and green transformation.

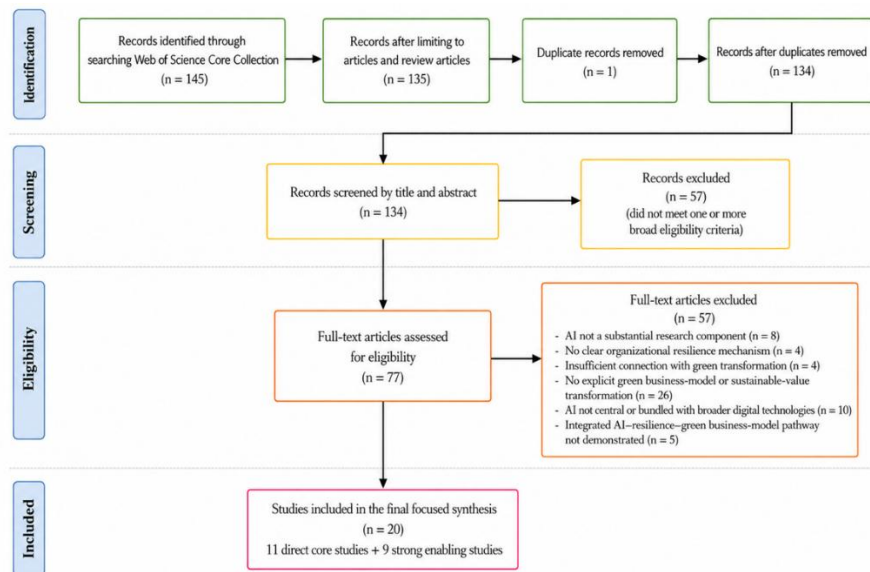


Figure 1 - PRISMA flow diagram of the study-selection process

The publication profile confirms that this is a recent and interdisciplinary research area. One study was published in 2023, seven studies appeared in 2025, and 12 were published in 2026. No study from 2024 met the refined eligibility criteria, and the 2026 results represent only partial annual production because the search was conducted on June 30, 2026. The 20 studies were published in 17

journals and combine research from strategic management, sustainability, innovation, supply-chain management, engineering management, digital transformation, and business model innovation.

Table 1 presents the publication profile and the principal thematic characteristics of the focused corpus.

Table 1 - Profile and main thematic findings of the focused corpus

Dimension	Category	Studies	Percentage
Publication year	2023	1	5.0%
	2025	7	35.0%
	2026	12	60.0%
Document type	Research articles, including early-access articles	19	95.0%
	Review articles	1	5.0%
Selection tier	Direct core studies	11	55.0%
	Strong enabling studies	9	45.0%
AI mechanisms	Predictive analytics and forecasting	8	40.0%
	AI capability and organizational adoption	6	30.0%
	Intelligent automation	5	25.0%
	AI-enabled decision support	4	20.0%
	Knowledge and organizational learning	4	20.0%
Resilience capabilities	Anticipation	10	50.0%
	Absorption and recovery	15	75.0%
	Adaptation and reconfiguration	17	85.0%
	Strategic transformation	18	90.0%
Green outcomes	Green or sustainable business model transformation	11	55.0%

	Circularity and closed-loop value	9	45.0%
	Green innovation	6	30.0%
	Sustainable and resilient supply chains	6	30.0%
	Resource efficiency and waste reduction	3	15.0%
	Low-carbon transition and emissions reduction	2	10.0%

AI-Enabled Organizational Resilience.

Predictive analytics and forecasting represented the most frequent AI mechanism, appearing in eight studies. These applications supported environmental sensing, demand forecasting, risk identification, predictive maintenance, resource planning, and the anticipation of supply-chain disruptions. Their contribution was particularly visible in studies on circular business models, sustainable manufacturing, green innovation, and carbon-constrained supply chains (Sjödin et al., 2023; Fernández-Miguel et al., 2025; AlDhaheri et al., 2025; Ahmed et al., 2026; Mehmood et al., 2026; Kaur et al., 2026).

Six studies treated AI as a broader organizational capability rather than as an isolated technical application. In these cases, the effects of AI depended on its integration into managerial processes, strategic decision-making, dynamic capabilities, leadership, and organizational structures. AI contributed to sustainable performance and business model innovation when firms were able to integrate information, reconfigure resources, and respond to environmental change (Wang et al., 2025; Sanchez et al., 2025; Anh et al., 2026; Chowdhury et al., 2026; Zhang and Dong, 2026; Sangnak, 2026).

Other mechanisms included intelligent automation, AI-enabled decision support, knowledge integration, organizational learning, machine learning, digital twins, and generative AI. Automation supported process coordination, resource allocation, and operational redesign. Decision-support systems facilitated supplier selection, scenario evaluation, disruption response, and sustainable planning. Knowledge-based AI applications helped organizations interpret information, share knowledge across functions, and translate technological insights into coordinated action (Al Halbusi et al., 2025; Zahoor et al., 2025; Alzeiby et al., 2026; Huang and Zhao, 2026).

The thematic synthesis identified four resilience capabilities. Anticipation appeared in ten studies and involved forecasting, environmental sensing, opportunity identification, and early warning. Absorption and recovery appeared in 15 studies and referred to organizational continuity, rapid resource reallocation, and recovery from operational or supply-chain disruption. Adaptation and reconfiguration appeared in 17 studies and involved changes in workflows, routines, supply relationships, resource combinations, and strategic priorities. Strategic transformation was the most frequent capability, appearing in 18 studies, and included green innovation, circular-economy adoption, sustainable business model innovation, organizational learning, and broader strategic change.

However, strategic transformation should not automatically be interpreted as complete green business model transformation. A study was coded as strategic transformation when it described substantial organizational change, while direct business model transformation required explicit evidence of changes in value creation, value delivery, value capture, or overall business design. The findings therefore indicate that AI strengthens organizational resilience through the interaction of technological and organizational capabilities. Algorithmic performance alone is insufficient; the value of AI depends on managerial interpretation, organizational readiness, knowledge integration, leadership, infrastructure, and the capacity to convert analytical outputs into action.

Contribution to Green Business Model Transition. Eleven studies, representing 55.0% of the focused corpus, established a direct connection between AI and green or sustainable business model transformation. These studies examined circular business model innovation, sustainable value creation, digital and circular business models, regenerative innovation ecosystems, and AI-enabled business model redesign (Sjödin et al.,

2023; Al Halbusi et al., 2025; Islam et al., 2025; Wang et al., 2025; Sanchez et al., 2025; Ahmed et al., 2026; Capatina et al., 2026; Alzeiby et al., 2026; Huang and Zhao, 2026; Anh et al., 2026; Sangnak, 2026).

The remaining nine studies provided strong enabling evidence. They showed that AI can support green innovation, resilient supply chains, organizational agility, sustainable performance, circular practices, and low-carbon transformation, even when changes in value creation, delivery, and capture were not analysed directly (Fernández-Miguel et al., 2025; Zahoor et al., 2025; Aldhaheri et al., 2025; Ashergawi et al., 2026; Chowdhury et al., 2026; Kaur et al., 2026; Mehmood et al., 2026; Xin et al., 2026; Zhang and Dong, 2026).

Circularity and closed-loop value appeared in nine studies. AI supported circular transformation through knowledge integration, resource visibility, waste reduction, supply-chain coordination, digital servitization, and circular business-model configurations. Green innovation and sustainable or resilient supply chains appeared in six studies each. In these contexts, AI improved organizational learning, eco-innovation capabilities, adaptive decision-making, visibility, planning, flexibility, and coordination under environmental and operational uncertainty. Resource efficiency and waste reduction appeared in three studies, while low-carbon transition and emissions reduction appeared in two.

These findings reinforce the distinction between operational sustainability and green business model transformation. An organization may use AI to improve forecasting, reduce waste, optimize production, or strengthen supply-chain continuity without changing its underlying business model. Such improvements enhance environmental and operational performance, but they do not necessarily alter the organization's value proposition, stakeholder relationships, revenue logic, or value-capture mechanisms. Green business model transformation occurs when AI-enabled resilience capabilities support more fundamental changes, such as circular value propositions, digitally enabled service models, regenerative business ecosystems, sustainable collaboration, and organizational configurations designed around environmental value.

Barriers, Research Gaps and Integrated Framework. The reviewed studies indicate that the effects of AI on resilient green transformation are shaped by several technological, organizational, and institutional conditions. Data availability and quality, technological infrastructure, system interoperability, leadership support, employee capabilities, organizational agility, knowledge integration, cybersecurity awareness, and governance influence whether AI adoption produces lasting results (Table 2).

Table 2 - Integrated thematic framework for AI-driven organizational resilience and green business model transition

AI capability	Resilience contribution	Green transformation outcome	Main enabling and limiting conditions
Predictive analytics and real-time monitoring	Anticipation, environmental sensing, risk identification and preparedness	Sustainable planning, disruption prevention, emissions monitoring and improved resource allocation	Data quality, interoperability, analytical skills and model interpretability
Intelligent decision support	Absorption, recovery and rapid organizational response	Operational continuity, sustainable supply-chain coordination and improved environmental decisions	Managerial trust, transparency, accountability and human oversight
Intelligent automation and process optimization	Adaptation, workflow adjustment and resource reconfiguration	Resource efficiency, waste reduction, circular production and improved sustainable performance	Implementation costs, employee acceptance, technological dependence and system integration

Digital twins and simulation	Scenario testing, predictive maintenance and adaptive planning	Resilient production, sustainable manufacturing and circular value-chain design	Infrastructure requirements, cybersecurity, technical complexity and data availability
Knowledge integration and organizational learning	Adaptation, learning and strategic transformation	Green innovation, circular-economy adoption and regenerative organizational development	Leadership support, workforce capabilities, knowledge-sharing structures and absorptive capacity
AI assimilation, strategic agility and dynamic capabilities	Strategic reconfiguration and business model redesign	Sustainable value creation, circular business models and green business model transformation	Organizational readiness, strategic alignment, institutional support and governance
Generative AI and immersive digital technologies	Knowledge creation, experimentation and ecosystem transformation	Regenerative innovation ecosystems and digitally enabled sustainable business models	Ethical risks, transparency, uncertain returns and environmental costs of digital infrastructure

The framework suggests a sequential but non-automatic relationship. AI provides capabilities related to prediction, automation, monitoring, simulation, learning, and decision support. These capabilities strengthen anticipation, recovery, adaptation, and strategic transformation. Resilience capabilities can then support circularity, green innovation, sustainable supply chains, and business model redesign when they are aligned with explicit environmental objectives.

Several tensions also emerge. AI can reduce resource consumption in one process while increasing energy use and computing requirements elsewhere. Automation may strengthen continuity but increase dependence on complex technological infrastructures and external providers. Data-driven recommendations can improve responsiveness, but they also raise transparency and accountability concerns when decision-makers cannot adequately explain algorithmic outputs.

The review also identifies several research gaps. The evidence base is very recent, with 19 of the 20 studies published in 2025 or 2026, which limits longitudinal evidence on lasting transformation. Many empirical studies rely on cross-sectional surveys and structural equation modelling, so more longitudinal, quasi-experimental, mixed-method, and comparative designs are needed. Future research should also distinguish more clearly between operational sustainability, organizational resilience, green innovation, circular transformation, and green business model

innovation, while developing validated measures of AI-enabled green resilience that include environmental performance, organizational learning, cybersecurity, algorithmic transparency, human–AI collaboration, and the environmental footprint of AI technologies.

Conclusions

This systematic literature review examined how artificial intelligence contributes to organizational resilience in the transition toward green business models. Based on 20 studies indexed in the Web of Science Core Collection, the thematic synthesis showed that AI supports resilience through predictive analytics, intelligent decision support, automation, simulation, organizational learning, and broader organizational AI capabilities.

These mechanisms strengthen anticipation, absorption and recovery, adaptation and reconfiguration, and strategic transformation. In turn, they can support circularity, green innovation, sustainable supply chains, low-carbon operations, resource efficiency, and green business model redesign.

The findings confirm that operational improvement and green business model transformation are not equivalent. AI may improve efficiency, continuity, or environmental performance without changing how an organization creates, delivers, and captures value. Green business model transformation therefore requires the

deliberate alignment of AI capabilities with sustainability objectives, organizational strategy, dynamic capabilities, governance, and human oversight.

The study contributes by integrating artificial intelligence, organizational resilience, and green

business models into a single thematic framework. Further longitudinal and comparative research is needed to test these relationships across sectors, firm sizes, and institutional contexts and to develop reliable measures of AI-enabled green resilience.

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Comparative Research for Parking Management

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Abstract

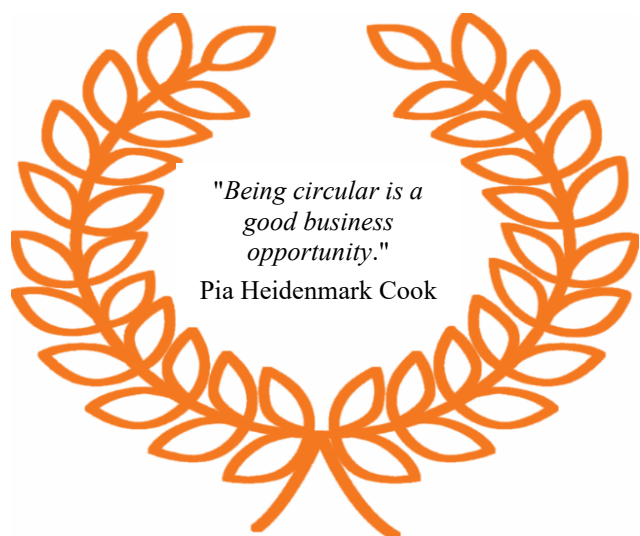
This article critically analyzes the management of a paid public parking lot located near a metro station in Bucharest, aiming to contribute to the debate on parking policies. The analysis is based on systematic observation conducted over a period of 64 days, focusing on usage patterns, occupancy rates, and compliance with the formal regulations of the parking facility. The results indicate a chronic underutilization of the infrastructure, with average occupancy values ranging between 45% and 50%, alongside the emergence of long-term informal usage practices tolerated by the administrator. The article argues that this disjunction between regulation and practice reflects a model of passive management oriented toward avoiding visible conflicts, which, between objectives and outcomes in public space administration, leads to the informal privatization of a public good and a reduction in the efficiency of urban mobility policy.

Keywords: parking management, public policy, urban governance

Introduction

In recent decades, public policies regarding parking have become a central instrument of urban mobility policies. Parking regulations are used to discourage car access to central areas, to support the use of public transport, and to reduce individual car travel. From this perspective, paid public parking lots are not merely technical infrastructures but genuine public policy instruments through which local authorities intervene in mobility behaviors and regulate the use of urban public space. However, the effectiveness of these instruments fundamentally depends on the coherence between formal regulation, implementation mechanisms, and everyday management practices.

In numerous urban contexts, parking policies appear to be characterized by institutional



ambiguity, selective enforcement of rules, and limited administrative capacity, and cities in former

socialist countries are no exception. Under these conditions, public parking lots often function differently from their stated purpose, through informal uses and inequities in access. Based on systematic observation conducted over a period of 64 days, this study examines the discrepancy between the formal, publicly displayed regulations of the parking lot and the actual usage practices.

The central argument of the critique is that the chronic underutilization of the parking lot, namely its use resembling a residential parking lot, does not necessarily indicate only low demand, but also a passive management model that reduces the effectiveness of public mobility policy. Through this approach, the article situates itself at the intersection of public policy analysis and urban governance studies, demonstrating that parking should be analyzed not only as infrastructure but as an institutional instrumental device, dependent on managerial decisions.

Literature review

Author of several highly regarded projects, Donald Shoup (1995, 2005, 2006, 2021) is recognized as an influential contemporary scholar in the study of urban parking policies and practices as instruments of public policy. He argues that parking is not merely an “ancillary service” for automobile use, but a central element of city governance and urban economics. In his view, parking policies have profound effects on traffic congestion, land use within urban perimeters, and socio-spatial inequalities. A key focus of Shoup’s work is the critical analysis of minimum parking requirements imposed by urban planners. In the article *An Opportunity to Reduce Minimum Parking Requirements* (Shoup, 1995), he demonstrates that these requirements lead to an oversupply of parking spaces, resulting in excessive land consumption, higher housing costs, and, in particular, encouraging private automobile use. Shoup argues that planners should abandon minimum requirements and allow the free market to regulate parking supply through pricing.

A key concept used by Shoup is “cruising for parking” (*Cruising for Parking*, Shoup, 2006),

referring to the time and resources drivers spend searching for free or underpriced parking spaces, which he characterizes as “underpriced.” He shows that this phenomenon significantly contributes to congestion and pollution, providing further support for the argument that appropriately balanced market-based pricing for parking can drastically reduce these negative externalities. In his volume *Parking and the City* (Shoup, 2021), in which he synthesizes previous lessons, he advocates for demand-based pricing, adding that parking prices should be set at levels ensuring that 1–2 spaces remain vacant per block at all times, and he considers this objective achievable through dynamic price adjustment. In his view, this approach not only improves parking efficiency but also supports sustainable mobility by reducing automobile dependency. Donald Shoup’s contribution lies in reconceptualizing parking, which should not be treated as a “technical problem” but promoted as an urban policy instrument. He emphasizes the role of prices, markets, and efficient planning as genuine policy tools for creating more functional and equitable cities.

Eric Inci is a recognized researcher for his contributions in the field of parking economics, analyzing how markets, prices, and regulations affect the use and efficiency of urban parking. In an extensive literature review on parking economics, Inci (2015) criticizes the treatment of parking as a free good. He argues that this approach significantly distorts efficient use of urban space, asserting that parking is, in essence, an intermediate economic good. In his view, the allocation of parking spaces should also be regulated through demand-responsive pricing policies (Inci, 2015). One of his key insights concerns land utilization and the external costs associated with parking. Inci suggests that parking occupies extensive areas, and its effects on real estate prices, traffic flow, congestion, and the environment are underestimated when spaces are provided for free or at low prices. According to Inci, variables influencing parking demand include location, duration of stay, temporal and spatial values, and traveler characteristics. He considers that parking demand is not perfectly inelastic,

meaning that prices can influence driver behavior (Inci, 2015). Therefore, he argues that when pricing policy is appropriately adjusted, it can reduce congestion, improve parking turnover, and enhance the overall efficiency of the urban transport system.

The concept of parking demand elasticity refers to the extent to which the use of parking spaces responds to changes in price, time, or access conditions. Following his literature review, Inci notes that parking is treated in the literature as a distinct economic good, whose demand is influenced both by monetary factors and spatial-temporal constraints (Inci, 2015). He observes that demand for long-term parking (residential or storage type) is more elastic than demand for short-term parking associated with commercial activities or services.

Donald Shoup also contests the hypothesis that parking demand is rigid or inelastic, he demonstrates that free or underpriced parking generates artificial demand, leading to overuse, long-term stays, and excessive searching for free or cheap spaces (Shoup, 2005). In his view, when parking prices are properly adjusted to local demand, driver behavior changes: they reduce parking duration, choose alternative modes of transport, or adjust their destinations.

Thus, in the article *Getting the Prices Right: An Evaluation of Pricing Parking by Demand in San Francisco*, Pierce and Shoup (2013) empirically demonstrate that differentiated and dynamic pricing can maintain an optimal occupancy rate of 85%, maximizing turnover and reducing conflicts among users. Consequently, parking demand elasticity represents not only an economic concept but also a useful instrument and a central argument for smart pricing policies and for critically evaluating passive or permissive management practices of public parking. Gregory Pierce and Donald Shoup have thus provided some of the most robust contributions to the analysis of parking pricing practices as a public policy instrument. They also explain how the effective implementation of these policies influences driver behavior and the efficient use of urban space. The authors advocate for the use of demand-based prices as a mechanism to correct distortions created by underpriced or free parking

spaces, which, in their view, additionally lead to spatial congestion, wasted time searching for a space (cruising), and inefficiencies at the urban scale (Pierce and Shoup, 2013).

Theoretical framework

Regarding the literature on public space management, Donald P. Moynihan (2004, 2005, 2008, 2010) is one of the most important contemporary theorists in performance-oriented public management. He argues that, over the past decades, public administrations in the United States and other Western democracies have widely adopted systems emphasizing measurement, transparency, accountability, and results in response to political, social, and institutional pressures demanding efficiency and responsibility. In *The Dynamics of Performance Management* (2008), Moynihan shows that governments have often failed to facilitate the organizational change necessary to transform field-collected data into effective decisions and institutional learning. He also explores the factors influencing how public managers use performance information, demonstrating that elements such as public motivation, organizational culture, administrative flexibility, and information availability affect the utilization of performance data, and that the mere existence of data does not guarantee performance improvements. Alongside other authors (Moynihan et al., 2011; Pierre, 2011; Manville, 2014; Carmona, 2019), he emphasizes that performance depends on the interaction between the external environment and internal management decisions, recommending a more integrated approach to performance management, which includes not only measurement but also the effective and adaptive use of information for learning and reform.

According to both classical and contemporary theoretical perspectives, urban governance is closely linked to concepts such as conflict and justice. The critical literature on urban governance provides a solid analytical framework for understanding tensions between formal regulations of public space and users' everyday practices. Manuel Castells (1977, 2010) conceptualizes the city as a space of structural conflict, in which state

interventions in urban infrastructures reflect power relations and logics of social reproduction. From this perspective, urban policies, including those concerning mobility and parking, are not neutral but mediate relationships among the state, capital, and urban users, often generating latent conflicts related to access and distribution.

Similarly, Susan Fainstein (2010) develops this critical approach through the concept of the “just city,” arguing that urban policies should be evaluated not only through criteria of efficiency or economic growth but also in terms of equity, democracy, and diversity. For her, the management of public spaces becomes problematic when it prioritizes the interests of privileged groups or produces subtle exclusions, even in the absence of overt conflict. Applied critically to public parking management, this perspective highlights the risk of transforming collective goods into semi-private resources disproportionately accessible to certain categories of users.

Maarten Hajer (2003) provides an explanatory framework for situations in which public policies operate in a state of “institutional void,” characterized by the absence of clear mechanisms for accountability and social coordination. Hajer emphasizes that, in such contexts, governance is exercised through informal practices, tacit arrangements, and avoidance of explicit political conflict. This approach is particularly relevant for analyzing public parking management, where the lack of active intervention by authorities leads to the tolerance of deviations from formal rules and the establishment of informal norms of use.

Finally, I consider the perspective of Sharon Zukin (1995, 2010), one of the most influential contemporary theorists specializing in urban studies, known for analyzing how power, culture, and the economy shape the form and function of cities through the correlation between power, space, and urban culture. A central concept in Zukin’s work (1995, 2010) is that urban space is mediated by cultural and economic forces; thus, power is not concentrated solely in institutions but is exercised through symbolic representations, cultural practices, and social relations that confer meaning to places. These theoretical perspectives have allowed me to conceptualize urban parking not only

as technical infrastructure but also as an arena of urban governance, where economic interests, institutional norms, and everyday practices intersect. They provide an appropriate theoretical framework for analyzing latent conflict, passive management, and their consequences on the equity and efficiency of urban mobility policies.

Research methodology

The research adopts a case study design, using non-participatory systematic observation as the main data collection method. The choice of this method is justified by the interest in the actual practices of parking usage, beyond the declarative statements of the involved actors. From a methodological perspective, observation allows capturing the effective management of the parking lot, highlighting discrepancies between formal regulations and everyday practices. The limitations of the method concern the impossibility of accessing the subjective motivations of drivers, an aspect that can be addressed in future research through semi-structured interviews. The interpretation of the results is conducted through the lens of the theoretical foundations presented and by comparing the observed factual data with the conclusions of a well-known case study conducted in San Francisco.

Case Study: Bucharest. Analyzing data obtained through systematic observation over 64 days at a public parking lot near a metro station in Bucharest, it was found that in this case as well, tacit privatization of public space can be observed.

The data were collected between September 30 and December 2, 2025, with 125 observation sessions conducted, distributed across various time intervals (07:00–23:00). The study covered 45 weekdays and 19 non-working days, including an important official event, the National Day. Additionally, during this period, the West Side Hallo Fest (October 24–26, 2025), a traditional annual cultural event attracting a large number of visitors, took place nearby. Moreover, the observations included a 7-day intermodal school holiday, allowing the detection of potential changes in parking behavior induced by these independent events. This approach enables distinguishing

between transient usage and stable occupancy of the parking lot.

The observed parking lot is located in the immediate vicinity of a metro station and a heavily trafficked tram line, serving as an important modal interchange within the transport infrastructure of Bucharest. The parking lot has 48 spaces, of which 3 are reserved for people with disabilities. The unit of analysis was the parked vehicle, identified visually and followed longitudinally based on recurrence of appearance. This approach allows differentiating between transient use and stable occupancy.

Collected data included the number of vehicles present, their frequency of appearance, temporal intervals of use, as well as qualitative observations regarding interactions, potential conflicts, presence of authorities, and measures taken. Occupancy rates were calculated by relating the average number of vehicles observed to the total capacity of the parking lot.

Analysis of occupancy rates indicated relatively consistent use of the parking lot throughout the observed period. In October 2025, the morning average was approximately 22 vehicles (45.83% occupancy rate), and in the evening 21.67 vehicles (45.14% occupancy rate). On weekends, morning averages were slightly higher (51.72%) compared to evenings (49.16%). For the entire October–November 2025 period, the average occupancy rate remained stable, with similar values in the morning and evening, regardless of the type of day, and during the students' short vacation a slight decrease in occupancy was observed, without significantly altering the general patterns.

An extreme case was represented by the West Side Hallo Fest (October 24–26, 2025), when, on each day of the festival, the number of vehicles present in a single day exceeded the nominal capacity of the parking lot, with occupancy consistently over 90%. For instance, on October 25, 77 distinct cars were observed, and on October 26, 85 cars. Many of these vehicles were seen for the first time, generating a high rotation rate and shorter parking durations.

From the overall study perspective, the West Side Hallo Fest represented an extreme case, generating a different pattern of parking usage

compared to the rest of the period. This behavior occurred due to an exceptional influence caused by tens of thousands of people arriving in the area within a very short time, flooding the zone with parking demand for several thousand vehicles compared to regular days.

The collected data indicate an average occupancy between 45% and 50%, with the parking lot predominantly used by subscribers, a situation contradicting the type of parking and its regulatory norms. In fact, the only period during which this parking lot functioned according to its formal purpose, providing parking for a large number of cars with high rotation and short-term presence, was during the festival. This also generated a noticeably better economic outcome, as these new users paid hourly, unlike the regular subscribers.

Case Study: San Francisco. A key element in the work of Pierce and Shoup (2013) is the SFpark program in San Francisco, used by the authors as a case study to demonstrate the benefits of dynamic pricing. By adjusting prices according to occupancy levels, the authors show that cities can achieve a target occupancy of 85%, maintaining parking turnover and reducing congestion and problematic parking behaviors (Pierce and Shoup, 2013).

The study *Getting the Prices Right*, conducted by Gregory Pierce and Donald Shoup (2013), evaluated the impact of the SFpark pilot program in San Francisco, which implemented dynamic pricing for on-street parking. The study's conclusions highlight positive effects in reducing average search times for parking (cruising) and a decrease in the total estimated distance traveled by drivers during cruising in program areas. The researchers found that the SFpark program improved occupancy rates toward the target interval of 60–80%. They also noted that price variation did not record significant average increases. Public parking efficiency increased by over one-third (38%) through higher turnover, while city revenues remained stable. However, although prices were frequently adjusted through a trial-and-error method (based on demand), prices remained almost unchanged: "Prices increased in 32% of cases, decreased in 31%, and remained the same in 37%, with almost no change in the average price" (Pierce & Shoup, 2013, p. 72). Prices were adjusted according to the

time of day: “Each block has different prices in three periods of the day (before lunch, from lunch to 15:00, and after 15:00)” (Pierce and Shoup, 2013, p. 69).

The authors also emphasize that pricing policy should be accompanied by transparency measures and communication to the public, so that drivers understand the rationale for adjustments and can predictably adapt their behaviors. They discuss the issue of equity in access to parking spaces, showing that well-calibrated demand-based pricing can, contrary to expectations, create a balance between accessibility and efficiency, eliminating underutilization and improper use of parking spaces and adding benefits through “traffic decongestion and, therefore, improvement of life for all public transport users, pedestrians, and cyclists” (Pierce and Shoup, 2013, p. 79).

Results of research

A key element of the governance rules of the analyzed parking lot is the differentiated day/night usage regime. The parking lot is not designed as a residential parking facility and does not provide for long-term daytime parking. The formal regime requires hourly payment during the day and the existence of a subscription exclusively for the nighttime period, with the intrinsic obligation to vacate spaces during daytime hours.

Observation data, however, indicate a systematic deviation from this regime. Subscriber vehicles, which should only use the parking lot at night, remain parked during daytime hours as well, occupying spaces quasi-permanently. This practice is not sanctioned by the parking administrator, and the absence of additional charges for daytime use effectively transforms the parking lot into an informal residential parking facility. This transformation does not appear to result from an explicit public policy decision, but rather from the systematic tolerance of deviations from the formal regime. In this sense, the parking administrator becomes a passive actor in the informal privatization of public space. The nighttime subscription thus acquires the meaning of an extended right of use, beyond its contractual limits.

The location of the parking lot near a metro station in a mid-city area suggests that the infrastructure was designed to serve a park-and-ride logic, with users leaving their vehicles on the relative periphery of the city and continuing their journey by public transport. Observations, however, indicate that this function is only partially fulfilled. The use of the parking lot by a small number of subscribers limits access for transient users and significantly reduces vehicle turnover. Consequently, the parking lot loses its function as mobility infrastructure and is reinterpreted as an extension of private residential space. This informal privatization directly affects system efficiency and contributes to the structural underutilization of the parking lot relative to its declared objectives.

Based on longitudinal observation, several categories of parking behavior were identified, leading to a typology of these public parking usage behaviors:

- **Stored vehicles** – cars parked for very long periods, up to 30 days or even for the entire duration of the study, without being moved.
- **Vehicles used for non-residential purposes** – including cars used as storage for commercial activities or as public display for sale.
 - **Subscriber vehicles** – characterized by quasi-permanent presence, with three subtypes:
 - a) predominantly nighttime and weekend presence;
 - b) exclusively daytime presence on weekdays; and
 - c) presence during most observed intervals.
 - **Vehicles in transit** – cars observed only once or sporadically, whose use of the parking lot does not form part of a stable routine.

The results indicate a clear lack of satisfaction among drivers in transit with the fixed-price parking rules, expressed through reduced accessibility to the service. In terms of frequency, 18–20 vehicles were observed daily. These vehicles fall into the first three categories of the typology and form the financial basis of revenue obtained through subscription fees. Practically, these vehicles occupied between 37.5% and 42% of the parking space, representing an informal form of privatization. Paradoxically, in opposition to the park-and-ride logic, the category of vehicles in

transit was the least represented, with the notable exception of the period during the West Side Hallo Fest event. The results also suggested passive management by the parking administrator, content to report monthly revenue from subscriptions covering approximately 40% occupancy, showing no concern for driver dissatisfaction or for fulfilling the parking lot's role as a modal transport node.

Although observation did not reveal open conflicts or direct confrontations between drivers, the analysis indicates the existence of a latent, structural conflict between users and the parking management authority. This conflict manifests through strategies of rule avoidance, long-term occupation of spaces, and use of the parking lot for purposes incompatible with its declared function.

This particular type of conflict does not occur between drivers competing for space under scarcity conditions. It is a state of conflict between the institutional logic of turnover and the logic of stable users, generated by a focus on stability and cost minimization. "Subscriber" vehicles, cars used as storage, or as advertising supports are concrete expressions of this tacit conflict. Faulty parking management accentuates these tensions. The lack of corrective interventions in extreme situations, such as temporary urban events, leads to punctual overloading of the parking lot and its use beyond nominal capacity. At the same time, during ordinary periods, persistent underutilization indicates the system's inability to attract transient users and ensure rotation of parked vehicles.

In this sense, the absence of visible conflict can be interpreted as an indicator of normalized deviations from rules and tacit acceptance of an informal usage regime. Deviations from the norm become the informal norm, and the parking lot thus functions in a grey area between a regulated public service and a common resource captured by a restricted group of users.

The limitations of the method relate to the author's limited administrative capacity and the lack of access to the subjective motivations of drivers, an aspect that could be addressed in future research through semi-structured interviews. Validation through subsequent studies is thus recommended and necessary.

Discussion

The management of public parking represents an intersection between public policy, urban sociology, and institutional governance (Carmona, 2019). In theory, parking facilities are not merely physical infrastructure but also instruments for regulating mobility, ensuring equitable allocation of urban space, and managing conflicts among different users (Shoup, 1995; Inci, 2015; Pierce and Shoup, 2013). Urban policies, including fees, time limits, and permits, are designed to balance economic efficiency, accessibility, and social equity. However, the implementation of these policies often encounters contradictions between formal rules and informal practices. These social dynamics have been theorized by Henri Lefebvre through the concept of the production of space. In his seminal work *The Production of Space* (1991), Lefebvre challenges the view of space as a neutral framework or backdrop for human action, arguing instead that space is produced through social practices, power relations, and historical processes (Lefebvre, 1991).

For Lefebvre, space is not merely a "place" but a set of socio-material relationships that reflect and reinforce existing power structures. He argues that these three dimensions interact dialectically: planners design spaces according to bureaucratic rationalities, but users experience and reshape them through everyday practices. In this ongoing dialogue, urban space is constantly produced, reproduced, and contested. Applied to the study of public parking, Lefebvre's concept highlights how formally regulated spaces (e.g., paid parking) can be reinterpreted and reconfigured through informal social practices (e.g., abusive occupation or tacit privatization), generating a discrepancy between designed and lived space.

Viewed through Castells' (1977) perspective, these observations reflect the structural tension between formal rules and actual space usage: although the parking lot is intended for rapid turnover of transit vehicles and hourly daytime payments, subscribers use the spaces during daytime hours, creating an overlap between formal access and informal practices, resulting in a form of latent conflict. Regarding the equity of parking allocation, analyzed through Fainstein's (2010)

lens, subscriptions privilege a narrow group of users, while other travelers/drivers who should use the parking lot for rapid transit to the metro are disadvantaged.

Thus, the current public policy of the parking lot produces subtle inequities, oriented more toward maintaining the status quo than maximizing equitable access. The persistence of this type of public policy can be explained using Hajer's (2003) perspective: the institutional void created by passive management allows subscribers to transform the transit-designated parking into *de facto* residential parking. It can be assumed that a lack of monitoring is evident, as formal rules are not sufficiently integrated into practice, and governance is exercised through informal, tacit norms, which maintain these practices relatively stable.

The presence of "subscriber" vehicles and those used as storage suggests the transformation of the paid public parking into an extension of private space, despite formal regulations. Extreme cases generated by temporary urban events highlight the fragility of the balance between supply and demand and the high potential for conflict. At the same time, the relatively stable occupancy rate during ordinary periods indicates the existence of well-established routines.

This analysis thus combines quantitative observations (occupancy of only 45–50%) and qualitative observations (subscriber practices and passive management) with a critical perspective on urban policies, highlighting how contradictions between formal regulations and everyday behaviors generate inefficiency, inequity, and dissatisfaction, while also revealing opportunities for reconfiguring public policies.

The Bucharest case study extends existing literature on urban governance and parking management through an empirical analysis of the institutional void and latent conflict between formal rules and everyday practices. From a sociological perspective, the study shows that subscriptions and passive management are not merely a technical issue but also a social phenomenon, reflecting how individuals adapt to and negotiate urban rules. Effective public policies must recognize this social dimension, integrating both economic instruments and governance and urban behavior interventions.

The main contribution lies in highlighting a specific mechanism: subscriptions, combined with passive management, generate the tacit privatization of public space, transforming temporary paid parking into a semi-private good. This finding bridges Castells' (1977, 1996) theories of urban conflict, Fainstein's (2010) theory of urban justice, and Hajer's (2003) framework of governance under institutional void, demonstrating how the interaction between rules, practices, and formal oversight produces concrete effects on equity and policy efficiency. Furthermore, the study suggests that urban policy evaluation should simultaneously integrate analysis of actual occupancy, informal practices, and institutional management, providing a theoretical and methodological model applicable to other cities facing public parking dilemmas.

By integrating the institutional dimension and implications for public policy, the article demonstrates the sociological relevance of studying urban parking as an indicator of the relationship between the state, the citizen, and public space. The research is exploratory in nature but provides a solid foundation for future comparative analyses and the development of urban policies aimed at equitable and efficient use of parking infrastructure.

Conclusions

The results of this study indicate the need for a recalibration of public policies regarding paid urban parking, particularly in the outer and middle zones of the city, especially near public transport hubs. In the case of the analyzed parking lot, the central issue is not the lack of infrastructure or insufficient demand, but rather the failure of management in implementing the differentiated day/night usage regime. The specialized literature also shows that such dysfunctions are not exclusively the result of individual driver behaviors but reflect the limits of governance and public management of urban spaces. The study suggests that differentiated pricing policies, aligned with urban governance principles, as well as flexible regulation, could optimize the occupancy of public parking and reduce social tensions.

The implementation of active governance measures, such as stricter control of parking duration, adjustment of tariffs according to demand (Shoup, 2021; Pierce and Shoup, 2013), and the integration of smart technologies (Elsonbaty and Shams, 2020; Alam et al., 2023), could increase efficiency and equity. Differentiated pricing and active monitoring could discourage long-term occupation of spaces intended for rapid turnover and facilitate access for transit vehicles, thereby contributing to better utilization of these public resources.

The main contribution of the study lies in conceptualizing the parking lot as a space of informal governance, where the absence of visible conflict masks a process of institutional delegitimization and everyday privatization of public space. From this perspective, low parking utilization does not merely reflect low demand but also the failure of regulatory and control mechanisms.

This research emphasizes the integration of power, conflict, and spatial production dimensions in the analysis of parking management and proposes the development of an integrated framework for evaluating parking policies, combining empirical analysis of occupancy, user behavior, and institutional management. This analytical mechanism can be replicated in other urban contexts with similar issues, such as public policies concerning urban planning and land use. It must continuously consider the specific developments of the local urban culture and the principles of accessibility, transparency, and equity. These recommendations are reinforced by Sharon Zukin's observations, which highlight how the transformation of urban space is often culturally justified, not merely economically, creating a "legitimate urban aesthetic" that conceals unequal conditions of access and participation (Zukin, 2010).

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Mapping the Structure of Green Business Models and Sustainability in Higher Education

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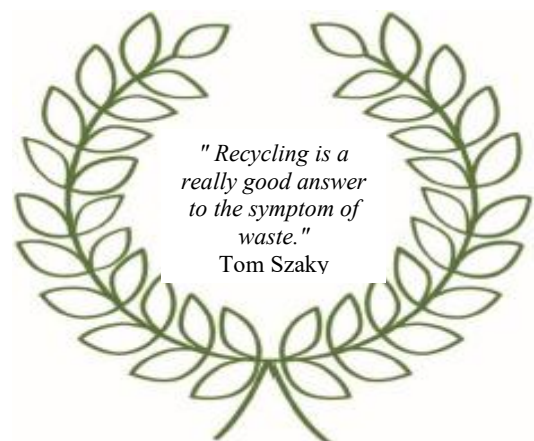
Abstract

This study maps the intellectual structure of scientific literature at the intersection of green business models (GBMs) and higher education institutions (HEIs), identifying dominant research streams and critical knowledge gaps that constrain GBM operationalisation in the sector. A bibliometric co-occurrence keyword analysis was conducted using VOSviewer (v.1.6.20) on a corpus of 458 articles extracted from the Web of Science Core Collection (2021–2026). Three clusters and a thematic intersection corpus were identified and systematically interpreted against the European sustainability regulatory agenda, CSRD, ESRS, EU Taxonomy, and the Green Deal. Two critical gaps are identified: the absence of intelligent data validation systems as an operational prerequisite for GBM performance measurement, and the underdevelopment of financial reporting transparency as a GBM legitimacy mechanism under CSRD/ESRS obligations.

Keywords: ESG governance, green business models, higher education institutions

Introduction

The transformation of higher education institutions (HEIs) into active agents of sustainable development has ceased to be a normative aspiration and has become an operational imperative. Under converging global and European pressures, from the United Nations 2030 Agenda for Sustainable Development (United Nations, 2015) and its seventeen Sustainable Development Goals, to the European Green Deal (European



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Commission, 2019), the Corporate Sustainability Reporting Directive (European Commission,

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2022), and the European Sustainability Reporting Standards (EFRAG, 2023), universities are no longer evaluated solely by educational and research outputs. They are increasingly assessed by the rigour with which they design, implement, and account for their sustainability strategies, both as institutional actors and as educators preparing the next generation of sustainability-literate professionals.

This dual positioning is structurally distinctive. Unlike corporations, HEIs simultaneously bear responsibility as *sustainability performers*, managing campus operations, governance structures, and financial resources in alignment with environmental and social criteria, and as *sustainability educators*, embedding ESG literacy, circular economy thinking, and green management competencies into curricula and research agendas. Giovanelli et al. (2021) were among the first to formalise this distinction within a green business model framework, arguing that the leadership role of higher education in sustainable development has been widely recognised, but that a paucity of studies follows a strategic perspective to explain how universities integrate sustainability across their activities. Rotondo et al., (2023) subsequently demonstrated that universities possess the vision, knowledge, and institutional power to lead the transition toward a more sustainable world, yet a research gap persists in understanding the implementation process, the tools required to move from design to operationalisation, and the challenges that may hinder this process.

The regulatory context has intensified these demands. The CSRD, in force since January 2023, extends mandatory non-financial reporting obligations to large public-interest entities, including qualifying universities, while the ESRS establish the applicable reporting standards. As later sections show, this creates both a diagnostic and a pedagogical burden for HEIs, particularly given documented gaps in regulatory literacy among students (Adamus-Matuszynska and Kolny, 2026).

At the global level, the GRI Universal Standards (Global Reporting Initiative, 2021) remain the dominant voluntary framework for sustainability disclosure in higher education. Yet

emerging evidence points to persistent data gaps and uneven reporting quality across institutions (Biloslavo and Schaebs, 2025), raising early questions about whether current practice reflects genuine transformation or superficial compliance.

As regulatory pressure intensifies and binding obligations progressively supersede voluntary frameworks, a systematic understanding of GBM operationalization in HEIs becomes indispensable. Existing bibliometric literature maps broad thematic areas in sustainability and higher education but does not position green business models as the central analytical lens connecting governance, data infrastructure, and financial reporting transparency, a gap this study addresses.

Two critical questions are underexplored: the role of intelligent data validation systems as operational prerequisites for GBM performance measurement, despite practitioner evidence that data gaps constitute the primary barrier to credible reporting; and whether financial reporting transparency functions as a constitutive condition of GBM legitimacy under CSRD/ESRS obligations. No existing study examines the integrated system through which HEIs simultaneously adopt GBM as strategic architecture, validate sustainability data through intelligent systems, and discharge accountability through transparent financial reporting, aligned with European regulatory requirements.

In response to this gap, the study is guided by three research questions:

RQ1 - What is the thematic structure of the 2021–2026 scientific literature at the intersection of green business models and higher education institutions, and which research streams have gained momentum in response to the European sustainability regulatory agenda?

RQ2 - To what extent does the existing literature address intelligent data validation systems as an operational prerequisite for credible green business model performance measurement in higher education institutions?

RQ3 - How does financial reporting transparency in higher education institutions function as an accountability mechanism within green business model frameworks, and what are the implications of European regulatory

instruments, CSRD, ESRS, and GRI Standards, for this relationship?

The remainder of the paper is structured as follows. Section 2 describes the systematic review protocol and co-occurrence mapping procedure. Section 3 presents the three-cluster intellectual structure and bridge analysis. Section 4 discusses research priorities and managerial implications. Section 5 concludes with contributions, limitations, and directions for future research.

Research methodology

The bibliometric corpus underpinning this study was retrieved from the Web of Science (WOS) Core Collection, one of the most rigorous and widely used databases for peer-reviewed scientific literature in management and business research. WOS was selected over alternative databases on the grounds of its comprehensive coverage of high-impact journals in management, economics, education, and environmental studies, the four disciplinary domains most directly relevant to green business models and their institutional dimensions.

The search query was constructed as a Topic Search (TS), interrogating title, abstract, author keywords, and Keywords Plus fields. The final query (TS7) was reached through six iterative formulations; earlier, more restrictive variants yielded corpora too small for meaningful co-occurrence analysis. Earlier, more restrictive variants, TS2 (100 records) and TS4 (24 records), yielded corpora too small to support statistically meaningful co-occurrence analysis. TS final was structured around two Boolean blocks connected by the AND operator:

- Block 1 captures the central thematic domain of green and sustainable business models, including: *green business model*, *sustainable business model*, *ESG*, *sustainability reporting*, *circular economy*, and *green management*;
- Block 2 anchors the search within the institutional context of higher education: *higher education*, *university*, *educational institution*, *education sector*, *higher education institution*, and *academic institution*.

Wildcard operators (*) were applied throughout to capture morphological variants. The raw query returned 1,320 records.

The raw corpus (1,320 records) was refined through four successive filters: publication window 2021–2026 (919 records); document type restricted to articles and reviews (819); WOS Research Areas limited to Business Economics, Education and Educational Research, Environmental Sciences and Ecology, Public Administration, and Social Sciences Other Topics (622); and WOS Categories restricted to Management, Business, Economics, Education and Educational Research, Public Administration, Environmental Studies, and Green and Sustainable Science and Technology, producing the final corpus of 458 documents. The search was frozen at 02 July 2026, 18:00 (Bucharest, Romania) for full reproducibility.

Co-occurrence mapping was performed using VOSviewer version 1.6.20, widely adopted for keyword network visualization in management bibliometrics. Nodes represent keywords, edges represent co-occurrence frequency, and spatial proximity indicates semantic relatedness. This architecture identifies the intellectual structure of a research field and the thematic boundaries between its constituent subfields (Grigore, Vlăduț and Nicolae, 2025).

Before running the co-occurrence analysis, a domain-specific thesaurus was constructed to normalise the keyword vocabulary of the corpus. The thesaurus performed three operations: (i) unification of morphological variants (e.g., *higher education institution* → *higher education institutions*; *sustainable business model* → *sustainable business models*); (ii) synonym consolidation (e.g., *ESG reporting* → *sustainability reporting*; *CSR* → *corporate social responsibility*); and (iii) elimination of high-noise generic terms (e.g., *trends*, *methodology*, *firms*) that carry no discriminatory thematic signal in the context of green business models research. Network construction parameters were set as follows: minimum keyword occurrence threshold = 20; minimum link strength = 0 (to maximise network connectivity); clustering resolution = 1 (VOSviewer default). These settings yielded 29 keywords with sufficient co-occurrence density to

form a stable network, subsequently distributed across 3 thematic clusters with a minimum of 5 items per cluster.

Since clustering in VOSviewer operates at the term level, article-level cluster assignment required a separate, deterministic scoring procedure. For each of the 458 records, the fields *Article Title*, *Author Keywords*, *Keywords Plus*, and *Abstract* were concatenated and scored against each cluster's keyword list using SUMPRODUCT-based string matching in Microsoft Excel (full procedure in Supplementary Material A). Each article was assigned to the cluster with the highest score; ties were classified as Thematic Intersection Papers (TIE), and articles scoring zero across all clusters were excluded from thematic interpretation.

Rather than a methodological residual, the TIE subset is interpreted as structural evidence of thematic convergence, documents whose conceptual vocabulary simultaneously bridges governance and reporting (C1), green business

model innovation (C2), and higher education sustainability (C3). The article-level distribution is presented in Table 1.

Results of research

Temporal distribution of the corpus. The 458 documents are distributed across the 2021–2026 interval as shown in Table 1. Publication volume grew consistently from 42 articles in 2021 to a peak of 109 in 2025, before a partial decline in 2026, attributable to the freeze date of 02 July 2026, which captures only the first half of the calendar year. The compound annual growth rate across the full period reflects a field in rapid expansion, consistent with the broader intensification of green business model research following the adoption of the European Green Deal (2019) and the post-pandemic ESG agenda acceleration.

Table 1 - Annual and cluster-level distribution of the corpus (N = 458)

Year	C1	C2	C3	TIE	Total
2021	11	9	7	15	42
2022	22	19	7	18	66
2023	25	16	7	22	70
2024	43	23	7	21	94
2025	40	30	8	31	109
2026*	34	25	3	15	77
Total	175	122	39	122	458

*Partial year: data frozen at 02 July 2026.

Cluster 1 (Governance, Reporting & Corporate Sustainability) is the largest, with 175 articles (38.2%), reflecting the dominant position of ESG and sustainability reporting research. Cluster 2 (Green Business Models & Sustainable Innovation) comprises 122 articles (26.6%), confirming the centrality of GBMs to this review. Cluster 3 (Higher Education Institutions & Sustainability Education) is the smallest discrete cluster (39 articles, 8.5%), though its weight increases substantially when the TIE corpus (122 articles, 26.6%) is considered. The TIE volume being equal to C2 is itself a structural signal: the green business model literature is deeply entangled with governance, reporting, and higher education

themes, rather than constituting an isolated research silo.

Co-occurrence Network Structure. The keyword co-occurrence analysis in VOSviewer identified 29 terms meeting the minimum threshold of 20 occurrences, distributed across 3 clusters, each capturing a distinct thematic dimension of the GBM–HEI intersection.

The co-occurrence network comprises 29 keywords distributed across three clusters. Cluster 1, Governance, Reporting & Corporate Sustainability, contains 11 terms: university (82, 321), sustainable development (61, 222), management (57, 206), challenges (43, 165), corporate social responsibility (42, 149),

sustainability reporting (39, 144), governance (38, 157), environmental sustainability (38, 108), ESG (39, 80), drivers (32, 97), and corporate governance (23, 79). Cluster 2, Green Business Models & Sustainable Innovation, contains 10 terms: circular economy (171, 382), innovation (44, 155), framework (42, 173), sustainability implementation (39, 186), sustainability indicators (27, 110), digital transformation (25, 96), sustainability education (21, 53), systems thinking (21, 76), education (22, 75), and models (21, 71). Cluster 3, Higher Education Institutions & Sustainability Education, contains 8 terms: higher education institutions (144, 448), sustainability

(130, 434), sustainable development goals (55, 186), strategy (28, 115), students (25, 84), bibliometrics (24, 89), green management (20, 68), and education for sustainable development (21, 67). For each term, values in parentheses represent occurrences and total link strength respectively.

Figure 1 presents the co-occurrence keyword network generated in VOSviewer, and colour coding distinguishes the three identified clusters: Cluster 1 - Governance, Reporting & Corporate Sustainability (red); Cluster 2 - Green Business Models & Sustainable Innovation (green); Cluster 3 - Higher Education Institutions & Sustainability Education (blue).

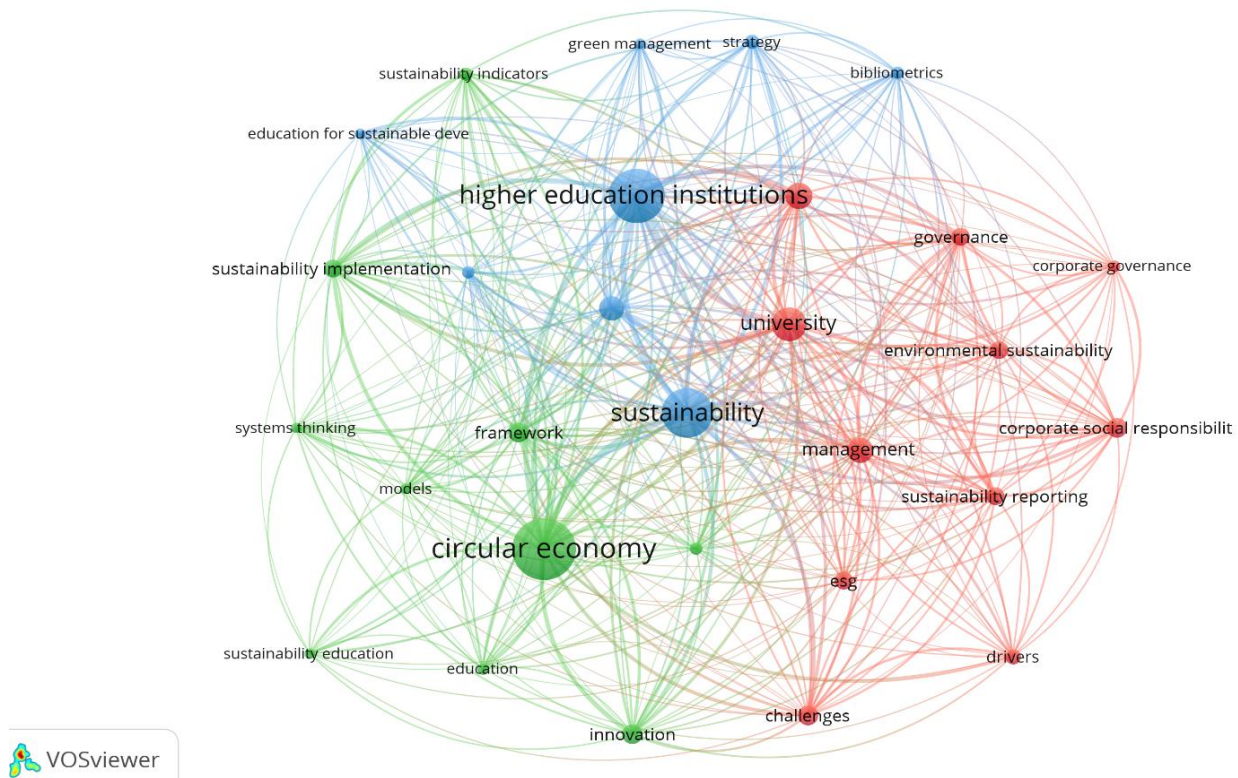


Figure 1 - Network visualization of the 29 terms across the 3 clusters

Cluster 1 - Governance, Reporting & Corporate Sustainability (N = 175)

Cluster 1 is the largest in the corpus, comprising 175 articles and 11 network terms organised around the logic of institutional accountability, non-financial disclosure, and corporate governance in the context of

sustainability. Its central terms, ESG (39 occurrences), *corporate social responsibility* (42), *sustainability reporting* (39), *governance* (38), and *management* (57), identify a body of literature in which green business model adoption is examined through the lens of what organisations disclose and how they are held accountable for their sustainability commitments.

Doltu (2006) demonstrates that risk and uncertainty management frameworks are foundational to institutional decision-making under conditions of strategic transformation, a perspective directly relevant to HEIs navigating the transition toward green business model adoption under evolving regulatory and governance pressures.

The co-presence of *university* and *sustainable development* within Cluster 1 is theoretically significant: it indicates that the literature treats higher education institutions not merely as educational environments but as organisations subject to the same governance and reporting expectations as corporations. Zdonek, Zdonek and Mularczyk (2025) confirmed this reading by analysing 53 ESG reports from sustainability-leading universities identified through the QS World University Rankings Sustainability 2025, finding that HEIs in Europe, North America, and East Asia are increasingly professionalising and institutionalising their sustainability reporting, a dynamic consistent with institutional isomorphism pressures. This finding has direct implications for the doctoral research agenda on financial reporting transparency in higher education institutions: the convergence of corporate ESG standards and university reporting practices is not a peripheral trend but a structural feature of the current literature.

The *drivers* and *challenges* co-occurring in this cluster reflect literature actively documenting the barriers to green business model adoption in institutional contexts.

Cluster 2 - Green Business Models & Sustainable Innovation (N = 122)

Cluster 2 constitutes the thematic core of this review, comprising 122 articles and 10 network terms that map the conceptual and operational architecture of green business models. Its dominant term, *circular economy* (171 occurrences, the highest raw frequency in the entire network), signals that the circular economy has become the primary theoretical vehicle through which green business model research is conducted in the 2021–2026 period.

Giovanelli et al. (2021) directly operationalised the sustainable business model concept in a higher education context, proposing a conceptual framework for diagnosing how Italian state universities integrate sustainability across their strategic and operational dimensions. Their analysis of 55 universities revealed six distinct sustainability integration profiles, from compliance-oriented to innovation-led models, and demonstrated that the sustainable business model construct can be meaningfully applied to HEIs, not only to for-profit firms.

The presence of *digital transformation* (25 occurrences) and *systems thinking* (21 occurrences) alongside *models*, *framework*, and *sustainability implementation* reveals that literature increasingly positions digital tools as enablers of green business model implementation rather than as independent phenomena. This framing is directly relevant to the doctoral research agenda on intelligent data validation systems in education: such systems can be understood as digital infrastructure components that enable HEIs to monitor, validate, and report on their green business model performance indicators in real time.

Cluster 3 - Higher Education Institutions & Sustainability Education (N = 39)

Cluster 3 is the smallest discrete cluster but carries the highest network centrality, as evidenced by the fact that *higher education institutions* (total link strength = 448) and *sustainability* (total link strength = 434) are the two best-connected nodes in the entire network, meaning that HEI-related research acts as the connective tissue binding the governance-reporting agenda of Cluster 1 and the green business model innovation agenda of Cluster 2.

The 39 articles in this cluster treat HEIs as the primary unit of analysis, examining how universities adopt, implement, and assess sustainability strategies. The alignment between energy efficiency strategies and the SDG agenda within higher education institutions has also gained traction as a research frontier. Todorova et al. (2025) demonstrate that energy efficiency initiatives in HEIs can function as a tangible operationalization of green transition commitments, providing an institutional-level

mechanism for SDG achievement beyond declarative sustainability policies.

Tracking and assessing SDG progress in HEIs requires standardised, comparable data systems, a structural need that, as this review argues, positions intelligent data validation as a functional prerequisite for HEI sustainability governance (see RQ2, Section 4.2). Frizon and Eugenio (2022) reviewed sustainability in higher education management and accounting (2014–2020), identifying seven influential author clusters and finding that curricular content, teachers, and students are the most studied objects, while sustainability in management education itself remains understudied relative to its importance, a gap this review addresses.

The *sustainable development goals* term (55 occurrences) co-occurring with *higher education institutions*, *students*, and *green management* reveals a literature that treats SDGs as the normative architecture within which HEIs construct their green business models. *Bibliometrics* (24 occurrences) appearing in this cluster confirms the methodological maturation of the field and validates the bibliometric approach adopted in the present study.

Thematic Intersection Papers - TIE (N = 122)

The TIE set comprises 122 documents, equal in size to Cluster 2 and representing 26.6% of the total corpus, a proportion that signals an advanced degree of thematic integration within the field. The annual TIE distribution (15, 18, 22, 21, 31, 15) shows a steady increase through 2025, with the 2025 acceleration particularly pronounced, suggesting that the convergence between governance, green business models, and HEI sustainability is not only a structural feature of the existing literature but also an accelerating research trend.

Pescador and Arzadun (2025) mapped the SDG–business model intersection through bibliometric and content analysis of 167 high-impact articles, identifying six structural clusters spanning frameworks, sustainable and circular business models, stakeholder involvement, and inclusive innovation and noting persistent gaps in cross-country knowledge exchange, particularly in

Ibero-America. Their work exemplifies the TIE logic, engaging governance, GBM design, and institutional context simultaneously. Their work exemplifies the TIE logic: it simultaneously engages governance (SDG reporting frameworks), green business model design (circular and sharing economy models), and institutional context (universities and public institutions).

Manchanda, Kakkar and Luthra (2025) explored sustainability education in management curricula through in-depth interviews with subject facilitators, students, and support staff, identifying ESG integration and green business leadership as the dominant emerging competency frameworks, and concluding that sustainability knowledge must be coordinated across all levels of institutional operations, a finding that bridges C1 (governance), C2 (green business model frameworks), and C3 (HEI education).

The TIE distribution across cluster boundaries confirms that the green business model literature is in a phase of internal integration: governance, innovation, and education are becoming operationally interdependent research domains, rather than independent subfields. This structural observation constitutes the empirical foundation for the research gap and research questions developed in the following section.

Discussion

RQ1: Thematic Structure and Regulatory Momentum.

The architecture of this study, based on three clusters identified through co-occurrence analysis, reflects a field of research undergoing rapid reconfiguration in response to European and global regulatory pressures. In Cluster 1, the co-occurrence of reporting on sustainability, governance, ESG criteria, and corporate social responsibility with “university” and “management” indicates that higher education institutions (HEIs) are treated as organizations expected to report on sustainability in ways that are structurally comparable to those of publicly traded companies (Sanchez et al., 2026; Lima et al., 2023). Cluster 2 highlights the emergence of conceptual and operational frameworks for implementing GBM in

higher education. Giovanelli, Rotondo and Ezza (2021) made one of the first contributions, contextualizing the sustainable business model within higher education across 61 Italian public universities. Rotondo et al. (2025) expanded this analysis to a longitudinal perspective, finding that a focus on sustainability has a negative short-term financial impact, thereby underscoring the need for robust long-term measurement frameworks rather than short-cycle financial indicators. Group 3 and the TIE corpus direct the analysis toward pedagogical and strategic dimensions, thus showing that all three research directions are gaining momentum as a direct response to the European regulatory agenda.

RQ2: Intelligent Data Validation as an Operational Prerequisite for GBM Performance Measurement

RQ2 addresses a structural gap in the literature: to what extent do existing scholarship treat intelligent data validation systems as an operational prerequisite for credible GBM performance measurement in HEIs? The answer, derived from systematic analysis of the 458-article corpus, is unequivocal: the literature does not address this prerequisite directly, but provides strong indirect evidence that its absence represents a critical impediment to GBM operationalisation.

The evidence for this structural gap is multi-layered. Brescia et al. (2026) identified fragmented data collection, limited comparability, and weak strategic anchoring as principal barriers to credible GBM performance measurement in HEIs. These obstacles point to the absence of systematic, validated data infrastructures necessary for GBM operationalisation.

Similar structural impediments are confirmed across multiple institutional contexts. Biloslavo and Schaebs (2025) examined how Joint Sustainability Reports (JSRs), built on the EU Voluntary Sustainability Reporting Standard (VSME), can serve as a cooperative and digitally supported framework to enhance transparency and comparability, but their qualitative interviews with experts from German and Austrian universities highlighted that *persistent data gaps* and *weak strategic anchoring* remain the primary barriers to

effective reporting, even when reporting frameworks are formally adopted.

The performance measurement dimension of this gap is equally documented. Alfirevic, Vrdoljak Raguz and Talaja (2024) arrived at a convergent conclusion from a different angle, proposing to automate the collection and dissemination of sustainability research findings through the implementation of a Current Research Information System (CRIS) as part of a broader roadmap for improving sustainability performance and reporting at the University of Split.

Curriculum-side evidence reinforces this diagnosis: comprehensive frameworks spanning multiple performance dimensions remain underexplored in the literature, representing a critical capability gap for GBM operationalization.

There is broad consensus in the literature on the need for reliable sustainability data in GBM implementation, but a lack of operational frameworks that treat intelligent data validation as a first-order institutional capacity. This study addresses that gap by proposing an intelligent validation system that ensures the sustainability data underlying GBM performance metrics are accurate comparable and audit-ready.

RQ3: Financial Reporting Transparency as an Accountability Mechanism within GBM Frameworks

RQ3 asks how financial reporting transparency functions as an accountability mechanism within GBM frameworks in HEIs, and what the implications of CSRD, ESRS, and GRI Standards are for this relationship. The corpus provides a rich, if fragmented, answer that underscore both the importance and the current immaturity of this relationship. The institutional prerequisites for financial reporting transparency in HEIs extend beyond regulatory compliance and include the foundational level of financial literacy within the academic community itself. Simandan et al. (2022) document the systemic challenges of financial education in Romania within a period of rapid societal transformation, highlighting that the capacity to produce and interpret credible financial disclosures is conditioned by broader literacy gaps that sustainability reporting frameworks, including

those mandated under CSRD, cannot address through regulatory instruments alone.

Financial disclosure is present in sustainability reports but often not integrated into a coherent governance architecture. The operationalisation of sustainability governance requires rigorous selection of financial performance indicators capturing both economic and non-financial dimensions. Barbu et al., (2019) provide a systematic analysis of widely used financial performance indicators, establishing foundations for a multi-dimensional performance measurement architecture aligned with ESG reporting requirements in European higher education for GBM implementation.

The gap between aspiration and institutionalisation is confirmed by a cross-sectoral comparison. Biloslavo and Schaebis (2025) show that VSME-based Joint Sustainability Reports enhance accountability through shared data collection and coordination, but identify absent common data standards as the binding constraint. Brescia et al. (2026) identify key challenges, publication practices, accessibility, comparability, and underdeveloped sustainability culture, proposing HEI-specific guidelines and stronger stakeholder participation.

Universities must balance fiscal responsibility with ESG imperatives while addressing student demands for ethical and transparent financial practices. GBM adoption responds to converging stakeholder expectations and regulatory pressure. Financial reporting transparency is not a compliance output but a constitutive condition of GBM legitimacy. HEIs adopting green business models must discharge financial reporting obligations with rigour aligned to GRI and ESRS standards; failure undermines the credibility of the entire sustainability architecture.

Adamus-Matuszynska and Kolny (2026), analysing the extent of Polish students' knowledge of ESG, CSRD, and EU Taxonomy, found that while students broadly recognise the ESG acronym and the CSRD directive, *substantial gaps remain in familiarity with specific regulatory documents and measurement indicators*, a result that reinforces the need for HEIs to function not only as reporters of sustainability but as pedagogical

agents capable of transmitting regulatory literacy. The dual role of HEIs, as sustainability actors and as educators preparing sustainability-competent professionals is ultimately what makes financial reporting transparency in this sector structurally distinct from its corporate equivalent.

Managerial and Policy Implications

The findings carry concrete implications for institutional actors within HEIs and for the national and European regulatory bodies that shape their operating environment.

For university leadership, sustainability officers, and curriculum designers, the evidence points to a shared strategic requirement: GBM adoption cannot rest on declared commitments alone but requires an institutional data infrastructure capable of supporting credible performance measurement (Brescia et al., 2026) and transparent reporting. The framework developed by Giovanelli et al., (2021) and extended longitudinally by Rotondo et al. (2025) offers rectors and sustainability officers an actionable diagnostic tool for locating their institution on the sustainability orientation – performance curve, a diagnostic made more urgent by evidence that sustainability orientation may exert short-term negative financial pressure. Curriculum designers and doctoral supervisors face a parallel imperative: embedding ESG regulatory literacy, data analytics competencies, and GBM thinking into postgraduate education, directly responding to the literacy gaps documented by Adamus-Matuszynska and Kolny (2026).

For national higher education authorities, the priority is developing HEI-specific sustainability reporting guidelines distinct from corporate CSRD requirements, addressing the current asymmetry between large public HEIs (within CSRD scope) and smaller institutions relying on heterogeneous voluntary frameworks (Alfirevic, Vrdoljak Raguz and Talaja, 2024). For European regulators and EFRAG, the evidence suggests that forthcoming ESRS sector-specific standards should explicitly address higher education as a distinct reporting entity, with indicators capturing HEIs' dual role as sustainability performers and sustainability

educators, a duality the existing GRI Standards do not fully capture.

Conclusions

In response to RQ1, the analysis revealed a tri-cluster intellectual architecture, governance and reporting, GBM innovation, and HEI sustainability education, bridged by a substantial thematic intersection corpus, confirming a field accelerating structurally in response to the European regulatory agenda (CSRD, ESRS, EU Taxonomy, Green Deal).

In response to RQ2, the literature shows broad consensus on the need for reliable sustainability data but has not yet produced frameworks that operationalise intelligent data validation as a dedicated institutional capacity, fragmented collection, limited comparability, and absent audit-ready architectures remain the primary barriers to GBM credibility

In response to RQ3, financial reporting transparency emerges not as a compliance output of GBM adoption but as a constitutive condition of its legitimacy: HEIs reporting without a validated data backbone risk producing documents that raise greenwashing concerns, a risk the CSRD and ESRS regulatory instruments now render materially consequential rather than reputational.

This study makes three contributions to GBM theory.

First, it provides the first bibliometric co-occurrence mapping of the GBM–HEI intersection as an integrated research field (458-article WOS corpus, frozen 2 July 2026), establishing a reproducible baseline for future longitudinal tracking, no prior study has positioned GBM as the central lens joining HEI governance, data infrastructure, and financial reporting.

Second, it extends GBM theory sectorally: applied predominantly in corporate and SME contexts, the framework is shown here to require structural adaptation for HEIs, which combine dual accountability (to public funders and sustainability stakeholders), a dual role (as sustainability actors and educators), and a non-profit value logic that renders short-term financial metrics insufficient for evaluating GBM impact.

Third, it proposes that the canonical GBM pillars, value proposition, value creation, value capture, require a fourth pillar for HEIs operating under CSRD/ESRS obligations: value verification, the institutional capacity to validate, audit, and certifiably report the sustainability data underpinning all GBM claims. Without value verification, a green business model collapses into a reputational instrument rather than a strategic architecture. Relatedly, this study reframes financial reporting transparency as an input condition of GBM legitimacy rather than an outcome of it: an HEI cannot credibly claim a green business model if its financial reporting fails to disclose, in standardised and auditable form, the financial implications of its sustainability strategy.

Three limitations merit acknowledgment. First, the corpus is restricted to WOS Core Collection, potentially excluding contributions indexed exclusively in Scopus, EBSCO, or grey literature. Second, the analysis relies on author keyword co-occurrence, which may underrepresent emerging concepts not yet stabilized as standard keywords. Third, the freeze date of 2 July 2026 excludes articles published in the second half of the year, and the reported growth trajectory should be interpreted accordingly.

Several directions emerge from these findings. Empirical validation of the three-layer GBM framework across institutional profiles (public research universities, universities of applied sciences, private HEIs) would test its generalizability. The concept of GBM data dependency warrants a validated scale for measuring institutional sustainability data readiness for CSRD/ESRS compliance. Comparative studies across EU member states would clarify how differing national transpositions of the CSRD shape HEI reporting practices and GBM adoption trajectories. Longitudinal research is needed on the relationship between GBM adoption, financial reporting transparency, and institutional performance, given evidence that short-term financial costs may require multi-year timeframes to yield measurable returns. Finally, curriculum development research should address the pedagogical priority of preparing sustainability professionals with both GBM literacy and CSRD-ready data competencies.

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Industry 5.0 and Sustainable Business Models in Digital Transformation

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Abstract

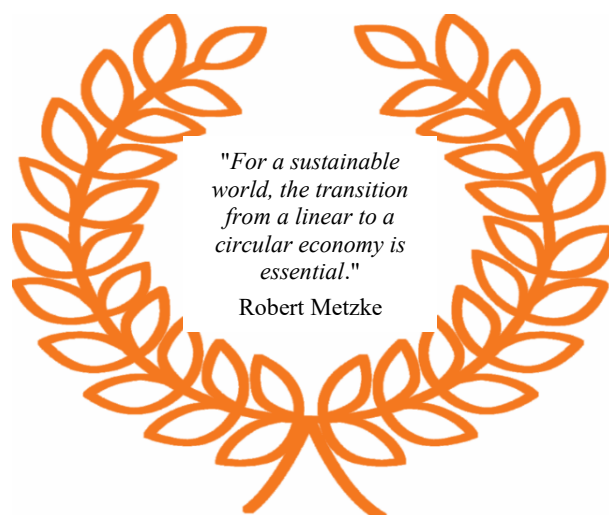
This article studies how sustainable business models are connected with Industry 5.0 and digital transformation. The paper uses a quantitative literature mapping approach based on 50 selected records, mainly focused on recent works from 2025 and 2026. The analysis was based on titles, keywords, and short abstracts. VOSviewer was used to create a keyword co-occurrence map and a density visualization. The results show that Industry 5.0 is strongly connected with sustainability, digital transformation, human-centricity, resilience, artificial intelligence, and green supply chain management. The results also show that sustainable business models are linked with circular economy, ESG, green innovation, and sustainable value creation. By reading up on the connections between digital technologies, sustainable strategies, and new business models, managers and researchers may have a better grasp of the current literature.

Keywords: ESG, Industry 5.0, sustainable business models

Introduction

Management of businesses today includes digital transformation. Data collection, task organization, mistake reduction, and decision assistance are all areas where businesses are turning to digital solutions. Products, services, schools, transportation, and government agencies are all undergoing this transformation. Additionally, it is related to sustainability as companies are increasingly expected to handle resources, waste, emissions, people, and long-term value (Breque et al., 2021; Hanelt et al., 2021; Kraus et al., 2021; Verhoef et al., 2021; Xu et al., 2021; Leng et al., 2022; Maddikunta et al., 2022).

Industry 5.0 provides a helpful framework for this transformation. The primary areas of emphasis in Industry 4.0 were digital systems, smart factories, and automation. These principles are retained by



Industry 5.0, which further emphasizes resilience, sustainability, and people (Breque et al., 2021; Xu et al., 2021; Leng et al., 2022; Maddikunta et al.,

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2022). In other words, cutting corners is not the sole reason to employ technology. Responsible business models, social value, and workers should all be supported by it as well.

Sustainable business models are important in this context. A company's value creation, delivery, and capture processes may be described by a business model. Environmental and social value are also components of a sustainable company plan. It takes a long-term look at the company's value generation, impact reduction, resource consumption, and partnering initiatives (Bocken and Geradts, 2020; Lüdeke-Freund, 2020; Lüdeke-Freund et al., 2020; Sinkovics et al., 2021). There has been new research linking sustainable business models to ESG (environmental, social, and governance), green innovation, digital transformation, and the circular economy (Ranta et al., 2021; Feng et al., 2022; Liu et al., 2025; Liu and Wang, 2025; Palmié et al., 2025; de Araujo et al., 2026).

Companies may benefit from digital transformation when they develop and oversee these types of business models. Data collecting, reporting, process management, and improved decision-making may all be aided by digital technologies. Additionally, they may provide light on the ways in which certain actions impact sustainability performance for businesses (Hanelt et al., 2021; Kraus et al., 2021; Verhoef et al., 2021). Green innovation, business innovation, and ESG performance may all benefit from digital transformation, according to recent research (Feng et al., 2022; Liu et al., 2025; Liu and Wang, 2025).

The circular economy is also associated with Industry 5.0. Less waste, more material reuse, longer product life, and closed resource loops are the pillars of the circular economy. Companies need to discover innovative methods to produce value with less resources, therefore this reasoning aligns with sustainable business strategies (Lüdeke-Freund, 2020; Lüdeke-Freund et al., 2020; Palmié et al., 2025; de Araujo et al., 2026). By using human-centered technology, smart manufacturing, digital platforms, and improved resource management, Industry 5.0 may bolster the circular economy, according to recent articles published in 2025 and 2026 (Rejeb et al., 2025; Samuels and Pelser, 2025; Shabur et al., 2025; Martínez et al., 2026).

Supply chains also place a premium on this subject. Suppliers, logistics, energy consumption, and material movements are inseparable from sustainable company models. Businesses may reduce their negative effects on the environment by using green supply chain management practices. It encompasses such activities as sourcing, manufacturing, distributing, emissions, waste, and collaboration among businesses (Jo and Kwon, 2021; Kassa et al., 2023; Tsolakis et al., 2023; Nozari et al., 2024). Supply chain planning and sustainability choices are being aided by artificial intelligence, machine learning, and decision-support systems, according to recent research (Barman, 2025; Teixeira et al., 2025; Vishwakarma et al., 2025; Drouzi and Rajaa, 2026).

Additionally, the aspect of management is essential. Sustainability is a multi-faceted issue. This issue also pertains to management. How to invest, disclose, choose partners, and strike a cost-benefit balance while still meeting environmental objectives are all decisions that managers must make. ESG has emerged as a valuable subject in this field since it establishes a link between environmental, social, and governance aspects and the reputation and performance of firms (Bao and Yang, 2025). Because it enables businesses to rethink their goods, processes, and strategies in a more environmentally friendly light, green innovation is a boon to this process as well (Alodat and Dong, 2026; Manshoven et al., 2026; Vallée et al., 2026).

If digital systems can simplify complex inputs into simple outputs, then they will be helpful, according to previous applied research. Decision tools, dashboards, machine learning models, and software applications may simplify otherwise incomprehensible data (Montiel et al., 2021; Galanti et al., 2023; Dragoi et al., 2025b; Buzducea et al., 2026; Dragoi et al., 2026c). Research in this area is not limited to eco-friendly company structures. Nonetheless, they stand by the same sensible principle. Digital transformation gains value when it enhances people's data understanding and decision-making capabilities.

Another important feature of Industry 5.0 is technology that is focused on humans. It is important that digital transformation go beyond only machines. In addition to helping individuals, it should simplify systems. Digital systems may be

created to meet human demands, according to recent applied research on teleoperation, local AI platforms, and gesture recognition (Dragoi et al., 2025a; Dragoi et al., 2026a). This idea fits Industry 5.0 because the human user remains part of the system.

Digital systems in industry are also important. Contemporary manufacturing processes use learning-from-demonstration techniques, digital validation, route planning, simulation tools, and robots. More control, safer procedures, and adaptable manufacturing are all possible with the help of these techniques (Cristoiu et al., 2026a; Cristoiu et al., 2026b; Dragoi et al., 2026b). Because they bridge the gap between technical operations and management choices, these solutions may facilitate digital transformation in a broader corporate setting.

It is necessary to quantify sustainability as well. Using "green" terminology is not enough for a business to claim sustainability. It needs to display metrics, ranks, comparisons, and outcomes. A number of factors and transparent ranking systems are often necessary for sustainability choices, according to recent studies on solar waste recovery (Nechita et al., 2026). Additional research on decision assistance and predictive analytics has shown that data-based models may aid firms in comparing choices and comprehending complex procedures (Masiello et al., 2024; Bojanowska and Kulisz, 2025; Zhang et al., 2025).

The recent literature is growing fast. Topics such as Industry 5.0, digital transformation, sustainable supply chains, ESG, green innovation, circular economy, sustainable business models, and digital transformation are covered extensively in papers released in 2025 and 2026. The result is a lively field that is also hard to keep up with. You may find out what phrases, topics, and research paths are most common in recent articles by creating a basic quantitative literature map.

The present study analyzes recent scientific works published in 2025 and 2026. The analysis focuses on titles, keywords, and main research themes. The purpose is not to make a full systematic review, but to offer a clear and simple map of recent research trends. Titles, keywords, and overarching study topics are the primary foci of the investigation. The goal is not to do a comprehensive

analysis. The objective is to provide a clear synopsis of recent developments in the field of study.

The connections to management, digital transformation, sustainability, and business make this kind of mapping valuable. It may reveal the ways in which ESG, green innovation, sustainable value creation, digital business strategies, the circular economy, and Industry 5.0 are all interconnected in the present day. It may also show management and researchers which subjects are getting more attention and which ways to go with future investigations.

This article mostly offers practical insights. It lays out the key concepts in a quantitative way and provides an overview of the most current studies. On top of that, it unites two perspectives on digital transformation and management. The article may help with future studies by revealing the most popular subjects in the titles and keywords of current scientific articles.

Methodology of research

This study used a quantitative literature mapping method. This method was chosen because the article does not test a software tool and does not use a company dataset. The goal is to review the most current research and determine the relationships between digital transformation, sustainable business models, and Industry 5.0.

The research was organized in two parts:

- The first part was used for background. It included scientific sources published after 2020. These sources were used to explain the main concepts, such as Industry 5.0, digital transformation, sustainable business models, circular economy, ESG, and green innovation.

- The second part was used for the actual mapping. Articles from 2025 and 2026 were the primary emphasis of this section. The article's goal of highlighting current research directions led to the selection of these publications. Instead of looking at older works, we looked at more recent scientific titles, keywords, and abstracts to see what people are now interested in.

The search was performed using open bibliographic sources. The main source was OpenAlex. Additional checking was done through Google Scholar and publisher pages, when needed. The search used combinations of the following

terms: Industry 5.0, sustainable business models, digital transformation, circular economy, ESG, green innovation, sustainable supply chains, and human-centered technology.

The selected works had to meet several simple conditions. They had to be written in English. They had to be connected with business, management, sustainability, digital transformation, or Industry 5.0. They also had to include enough bibliographic information, such as title, year, authors, source, and digital identifier, when available. Several types of works were excluded. Papers that were only technical and had no link with business, management, or sustainability were removed. Duplicate records were also removed. Papers with unclear titles, missing publication data, or weak connection with the topic were not kept in the final mapping set.

After screening, the final working corpus included 50 records. Each record was organized in a table with the following fields: title, year, source, DOI, keywords, and short abstract. This structure was used to make the data easier to check and easier to import into VOSviewer to create the keyword co-occurrence map. The map was based on text data extracted from titles, keywords, and abstracts. Due to incomplete author keywords in certain entries, this method proved effective. The analysis might catch more important phrases by combining the title, keywords, and abstract. The words were cleaned using a thesaurus file before the map was generated. We combined words that were really similar. One example is the grouping of several versions of Industry 5.0 under the same name. The use of meaningless, general terminology like "article," "study," "report," and "result" was

eliminated. The map now displays actual study topics rather than empty terms, thanks to this step.

We used complete counting in our VOSviewer study. Various variables were evaluated to determine the minimal number of occurrences. Using the parameters that provided a legible framework, the final map was produced. Producing a detailed map was secondary to highlighting the most obvious relationships between the key concepts.

The analysis focused on four simple outputs. The first output was the keyword co-occurrence map. The second output was the keyword density map. The third output was a table with the main thematic groups found in the selected literature. The fourth output was a short managerial interpretation of these groups.

The method has a practical character. It does not claim to be a full systematic review. It is a literature mapping study. Its role is to show which terms and themes are more visible in recent research and how they are connected. This is useful for understanding the current position of Industry 5.0 and sustainable business models in digital transformation.

Results and discussion

This section presents the results obtained from the quantitative literature mapping. The final corpus included 50 records connected with Industry 5.0, sustainable business models, digital transformation, circular economy, ESG, green innovation, and sustainable supply chains. The analysis was based on titles, keywords, and short abstracts.

The general structure of the corpus is presented in Table 1. This table shows the main input used for the mapping process.

Table 1 – Structure of the analyzed corpus

Item	Value
Final number of records	50
Main period for mapping	2025–2026
Background period	After 2020
Main data source	OpenAlex
Additional checking	Google Scholar and publisher pages
Main software used	VOSviewer
Main text fields used	Titles, keywords, abstracts
Main analysis type	Keyword co-occurrence mapping

(Source: processing based on records collected from OpenAlex, with additional checking through Google Scholar and publisher pages).

The corpus was built to give a recent view of the field. Older sources were used only for background and definitions. The mapping itself focused on recent works, mainly from 2025 and 2026. This choice was useful because the topic is new and changes fast. The first visual result is the keyword co-occurrence map generated in VOSviewer. This map shows how the main terms are connected in the selected literature.

Figure 1 shows that Industry 5.0 is the central term in the selected literature. It is strongly connected with sustainability, digital transformation, human-centricity, resilience, artificial intelligence, and green supply chain management. This result is expected because Industry 5.0 is not treated only as a technical topic. It is also linked with people, business decisions, and sustainable development.

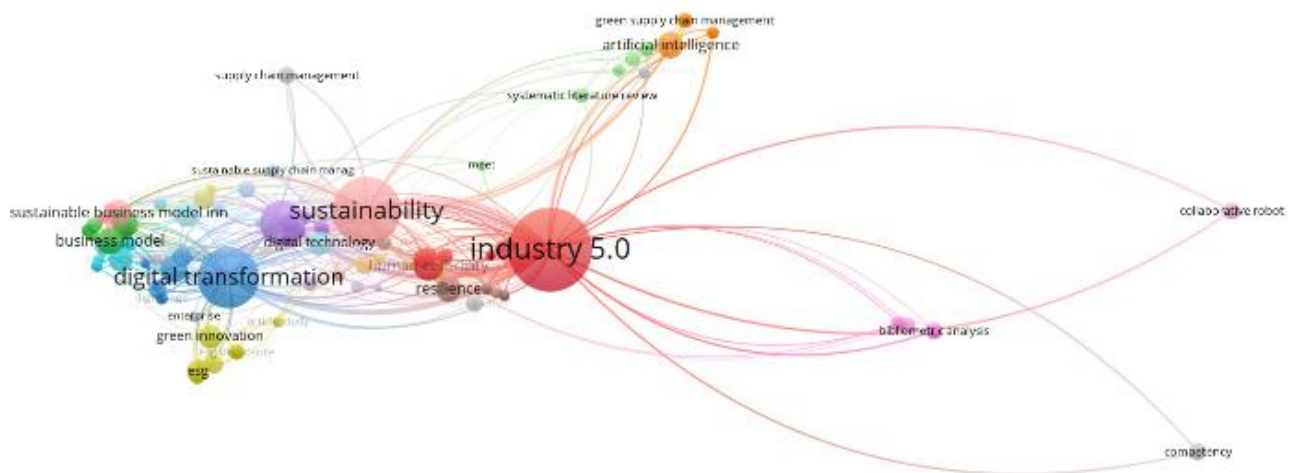


Figure 1 – Keyword co-occurrence map of the selected literature

The left side of the map is more connected with business and management terms. These include sustainable business model, business model, digital transformation, ESG, green innovation, and sustainable value. This shows that recent research connects sustainability with value creation and business strategy.

On the upper section of the map are the terms connected to artificial intelligence, green supply chain management and systematic literature review. This indicates that supply chain research is also relevant in this field. Digital technologies and intelligent procedures are frequently cited as being able to support sustainable judgments.

More precise terms like collaborative robot, competency and bibliometric analysis are placed on the right side of the map. The use of these expressions shows that the approaches of mapping literature and the cooperation between humans and machines are also components of Industry 5.0. They are small on the globe yet they nonetheless complement the larger concept of human-centered digital transformation.

The most prominent terms seen on the map are summarized in Table 2. This table is useful to better comprehend the figure.

Table 2 – Main thematic groups identified in the map

Thematic group	Main terms	Short meaning
Industry 5.0 and sustainability	Industry 5.0, sustainability, resilience, human-centricity	Industry 5.0 is linked with people, long-term stability, and sustainable development.
Digital transformation	digital transformation, digital technology, digitalization	Digital change supports new ways of working and managing organizations.

Sustainable business models	sustainable business model, business model, sustainable value	Business models are connected with value creation and sustainability goals.
Green innovation and ESG	green innovation, ESG, ESG disclosure	Firms use innovation and reporting to support cleaner strategies.
Supply chain sustainability	green supply chain management, supply chain management, global supply chain	Supply chains are part of the sustainability discussion.
Intelligent technologies	artificial intelligence, collaborative robot, digital technology	New technologies support decisions, production, and human-machine work.

Table 2 provides a number of directions that are connected to one another. The connection between Industry 5.0 and sustainability is the most important one. Second, we have the link between digital transformation and long-term company sustainability plans. Finally, we have the third point,

which is the supply chain's role in promoting sustainability via green innovation and ESG.

The density visualization is the second one. Figure 2 shows the most concentrated cluster of phrases in the chosen corpus.

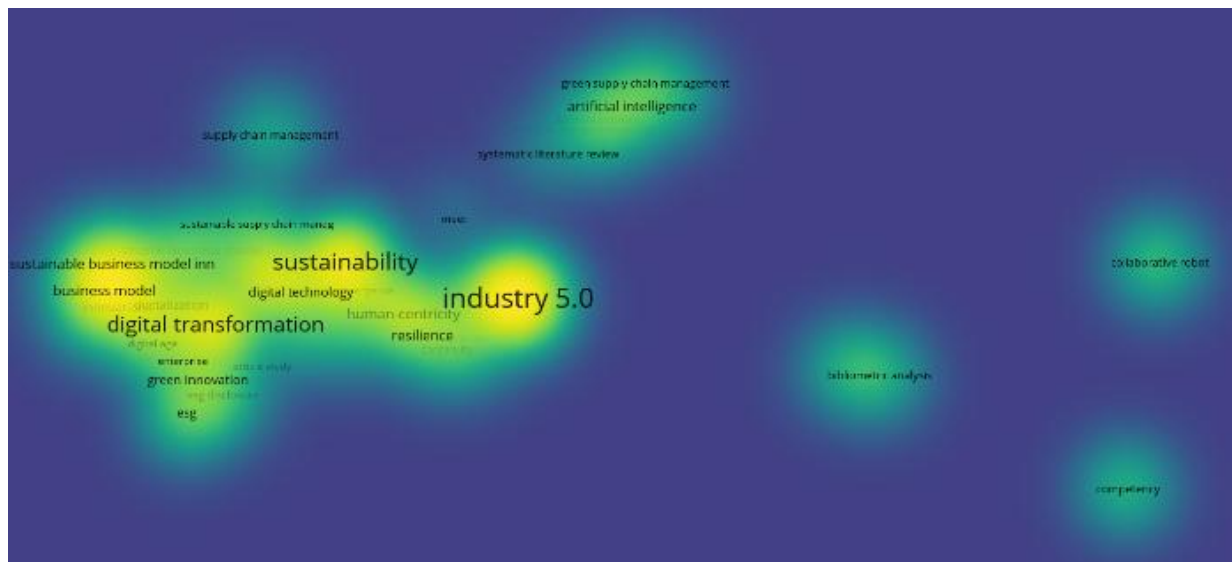


Figure 2 – *Keyword density visualization of the selected literature*

To see how dense the chosen corpus is with major phrases, see to Figure 2. Industry 5.0, digital transformation, sustainability, and sustainable business models are the strongest areas. This proves that the chosen literature is concentrated on a small number of related topics. Green supply chain management, artificial intelligence, ESG, and green innovation are the secondary yet visible paths, according to the density viewpoint.

On the left side of the map, there are additional words connected to business and management. Among them are ESG, green innovation, sustainable value, digital transformation, and

sustainable business models. What this means is that sustainability has been associated in recent research with value creation and business strategy.

At the very top of the map you may see terms like AI, green supply chain management, and systematic literature review. This further highlights the significance of supply chain research in this area. Sustainable decisions are often aided by digital technology and smart processes.

Collaborative robot, competence, and bibliometric analysis are some of the more specific keywords seen on the right side of the map. These definitions show that literary mapping methods and

human-machine cooperation are also part of Industry 5.0. Although they don't take up much room on the map, they do lend credence to the notion of a digital transformation focused on people.

Table 2 gives a list of the primary visible terms from the map. This table may assist to understand the figure better.

Table 3 – Managerial interpretation of the main themes

Theme	Managerial meaning
Industry 5.0	Companies should use technology together with human skills, not against them.
Digital transformation	Digital tools can help managers collect data and support decisions.
Sustainable business models	Firms need business models that create economic, social, and environmental value.
Circular economy	Companies can reduce waste by reusing resources and extending product life.
ESG	Firms must show more transparency in environmental, social, and governance actions.
Green innovation	Cleaner products and cleaner processes can support long-term competitiveness.
Sustainable supply chains	Sustainability depends on suppliers, logistics, resources, and collaboration.

The findings are shown in Table 3 and are both theoretical and empirical. From a managerial vantage point, they may also be understood. Practical company directives may be produced by translating the terminology found in the literature. Managers may use these recommendations to aid in the development of plans for digital transformation, sustainability efforts, and ecologically conscious corporate practices.

Furthermore, the results demonstrate that discussions on sustainable business strategies are not unique. In particular, they address ESG considerations, digital transformation, the circular economy, and supply chains. That is why an environmentally conscious business strategy must include more than just lip service to the cause. Management of resources, generation of value, and reporting on technical development are all included under this framework.

In addition, it is important to highlight the significance of technology that is designed with humans in mind. With the arrival of Industry 5.0, people are again actively participating in the digital revolution. Think from a fundamental automation point of view. Streamlining processes, enhancing decision-making, and fortifying companies are the three main goals of Industry 5.0 technology.

A further point to consider is that the map illustrates the development of digital technology and artificial intelligence in the literature. On the other hand, they are not the main focus. They are portrayed as tools that may assist the aims of businesses and initiatives related to sustainability. The significance of this cannot be overstated since the essay does not discuss technology in a vacuum. In its view, technology is an integral component of the development of business.

Reporting, trust, reputation, and environmentally friendly innovation are all parts of ESG, which is becoming more important according to the literature we looked at. It is important for firms to communicate and monitor sustainability. Claiming a company can weather the storm is insufficient. There has to be action, indications, and outcomes from the business.

All things considered, the map shows a straight path. New research links digital transformation to Industry 5.0 and sustainable company strategy. Green innovation, human centricity, digital transformation, sustainability, ESG, and supply chain sustainability are the most talked about subjects. These subjects provide the impression that this is a management and technically oriented field. That it makes use of electronic devices and intelligent networks qualifies as technological.

Managing business models, creating value, reporting, and strategy are all aspects that fall within its purview.

Conclusions

This study offered a straightforward quantitative literature map on digital transformation's sustainable business strategies and Industry 5.0. The fifty records included for the investigation largely pertained to modern works published in 2025 and 2026. Subjects included in the research included titles, keywords, and brief abstracts.

Sustainability and digital transformation are shown to be strongly tied to Industry 5.0, according to the findings. Additionally, the term map shows connections to human-centricity, resilience, AI, ESG, green innovation, and green supply chain management. Thus, Industry 5.0 is more than just a technological issue. The fields of business and management also touch on this.

Additionally, the mapping shows that there are many connections to sustainable business practices in the actual world. Sustainable value, green

innovation, environmental, social, and governance reporting, and sustainable supply chains are a few examples. This proves that businesses need more than just environmental signals. Measures, indications, and adjustments must be provided by the company.

By highlighting the most prevalent themes in the most recent research, the results are helpful to managers. Managers may use these ideas while developing plans for digital transformation and long-term sustainability. Additionally, researchers might use them to choose the following steps for their researches.

The study does have certain limitations. The corpus cannot be considered comprehensive due to its small size of 50 records. In addition, the investigation made use of bibliographic databases and VOSviewer text mapping. Expanding the scope of the research to include Scopus and Web of Science might provide more data.

While there are several caveats to the study, overall it provides a good overview of the current research trends in the field. This exemplifies the growing interdependence of people, digital transformation, sustainability, and sustainable business strategies.

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Developing a Business Model in Horticulture Through Agricultural Policy and Market Diversification

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Abstract

The article analyzes the recent evolution and performance of the horticultural sector, focusing on the impact of subsidy policies, the modernization of perennial plantations, and the diversification of markets in the context of geopolitical and commercial changes. The research is based on statistical, monographic, and comparative analysis methods. A case study is conducted on peach cultivation, highlighting trends in the reduction of cultivated areas, accompanied by increased productivity as a result of variety renewal and the application of modern technologies. An analysis of competitiveness through the lens of Porter's five forces model reveals the existence of persistent structural constraints, such as fragmented production, underdeveloped post-harvest infrastructure, and a concentration of exports on traditional markets. The results highlight the need to strengthen cooperation between producers, optimize subsidy mechanisms, and intensify efforts to access European Union markets in order to increase the long-term resilience and competitiveness of the horticultural sector.

Keywords: agricultural subsidies, agri-food exports, competitiveness

Introduction

The horticultural sector represents one of the most dynamic and strategic branches of agriculture in the Republic of Moldova, making a significant contribution to value added, rural employment, and agri-food exports (FAO, 2024; World Bank, 2024). Due to its high value-added potential, horticulture plays an important role in increasing farm incomes and supporting sustainable rural development.

Over recent decades, the horticultural sector has undergone profound structural transformations driven by economic transition, trade liberalization, and adaptation to the evolving requirements of external markets. For more than 30 years, the post-Soviet states served as the primary export destinations for Moldovan horticultural products.



"We cannot lose sight of the fundamental challenges facing future generations."
Niels B. Christiansen

The preference for medium-quality products, familiar logistics, and relatively favorable payment

conditions reduced incentives for exporters to diversify their markets.

However, the trade embargoes imposed by the geopolitical context have exposed the vulnerability of this concentrated export model. At the same time, the signing of the Association Agreement and the Deep and Comprehensive Free Trade Area (DCFTA) with the European Union created favorable conditions for the gradual reorientation of horticultural exports toward more stable and quality-demanding markets. This paper aims to assess how Common Agricultural Policy (CAP) instruments can be adapted to the specific structural characteristics of the Moldovan horticultural sector.

Research methodology

The research is based on a mixed methodological approach combining quantitative and qualitative methods. The study employs statistical and comparative analysis, trend analysis, the monographic method, documentary and regulatory analysis, as well as competitiveness assessment using Porter's Five Forces model. The informational base includes data from the National Bureau of Statistics (NBS), the Agency for Intervention and Payments in Agriculture (AIPA), the UN Comtrade database, reports from national and international institutions, and relevant regulatory documents.

This integrated approach allows for a comprehensive assessment of recent developments, performance trends, and the main constraints affecting the competitiveness and sustainability of the horticultural sector.

Results and Discussion

Investment dynamics. Agriculture continues to play an important role in the national economy,

providing employment for approximately 21% of the workforce. In recent years, investment dynamics in the horticultural sector have been shaped by a gradual process of technological modernization and capital deepening. Public and private investments have increasingly targeted the establishment of modern orchards, the rehabilitation and expansion of irrigation systems, the acquisition of advanced agricultural machinery, and the development of post-harvest infrastructure, including cold storage and sorting facilities.

These investments have contributed to higher productivity levels and improved product quality, facilitating better compliance with international market standards. The observed increase in yields despite the reduction in cultivated areas indicates a shift toward more intensive production systems, supported by technological upgrading and varietal renewal. However, investment activity remains uneven across producers, reflecting differences in access to financial resources and institutional support. The horticultural sector stands out for its significant multiplier effect on the economy, positively influencing processing, packaging, transportation, and marketing activities (Stratan A., Iatinsin T., 2022). During the period 2019–2023, agriculture accounted, on average, for approximately 40% of the Republic of Moldova's total exports, confirming the strategic importance of the horticultural sector in foreign trade (NBS, 2023). In 2023, the horticultural sector recorded a decrease compared to 2022 in the total areas of both stone and pome fruits. The total area of stone fruits decreased by 1.2%, while that of pome fruits decreased by 8%. However, the total fruit harvest during this period showed an increase (the total stone fruit harvest in 2023 increased by 24.5% compared to 2022, and the pome fruit harvest increased by 15.6%, see Table 1.

Table 1 - The area and yield of the horticultural sector for households of all categories

Years	2010	2020	2021	2022	2023
Orchards – total, thousand ha	115,2	137,3	135,2	133,6	130,7
<i>orchards stone fruit</i>					
Total area, thousand ha	39,3	42,4	41,2	41,2	40,7
of which, fructiferous, thousand ha	30,4	37,0	36,2	36,7	36,5

Gross harvest, thousand tonnes	91,5	147,4	182,7	156,0	194,3
Yield per hectare of fruit q/ha	29,0	39,1	49,4	41,2	52,9
<i>seed orchards</i>					
Total area, thousand ha	66,6	60,2	57,3	55,2	50,8
of which, fructiferous, thousand ha	58,8	53,8	51,8	50,5	46,4
Gross harvest, thousand tonnes	217,5	487,7	655,5	455,0	525,9
Yield per hectare of fruit q/ha	36,3	89,4	125,1	89,8	112,9

(Source: National Bureau of Statistics, 2024).

Statistical data indicate a reduction in the area cultivated with perennial plantations, accompanied by an increase in total output and productivity. This trend reflects the process of technological modernization, varietal renewal, and the removal of ageing plantations, supported through subsidy mechanisms. Public policies have stimulated investments in post-harvest infrastructure, agricultural machinery, and modern plantations, thereby contributing to improved economic efficiency and a reduction in post-harvest losses (Government Decision no. 840 of 18.11.2020). Over the past three years, the value of investments in agriculture and rural areas has been continuously increasing. Thus, in 2023, the total value of investments (post-investment and complementary subsidies) was 6.14 billion lei, representing an 8% increase compared to 2022 (Report AIPA, 2023). Furthermore, an important role is played by the geographical location, favorable climatic conditions, the potential for deepening relations

with the EU offered by the Association Agreement between the Republic of Moldova and the EU, including the component related to the Comprehensive and Enhanced Free Trade Area, relatively cheap labour, and government incentives, all of which have a qualitative and quantitative impact on the sector in diversifying horticultural product exports to new markets.

Case Study: Peach Cultivation

Peach cultivation represents a relevant case for analyzing recent structural changes within the horticultural sector of the Republic of Moldova. Statistical data reveal a declining trend in the total area under peach plantations over the analyzed period, reflecting the gradual removal of ageing and low-productivity orchards. At the same time, production dynamics indicate notable fluctuations in total output and yields, largely influenced by climatic conditions, technological practices, and the degree of plantation modernization see Table 2.

Table 2 - Trends in peach cultivation in the Republic of Moldova, during the period 2019-2023

Years	2019	2020	2021	2022	2023
Total area of peaches, thousand ha	6,6	6,1	5,6	5,4	5,1
of which, fructiferous, thousand ha	6,6	5,6	5,2	5,1	4,7
Gross harvest, thousand tonnes	22,3	18,7	18,5	20,5	12,8
Yield per hectare of fruit q/ha	35,2	32,2	34,1	39,1	27,3

(Source: National Bureau of Statistics, 2024).

Despite the contraction of cultivated areas, the observed changes suggest a gradual transition toward more intensive and technologically advanced production systems. The replacement of

obsolete plantations with modern varieties and the adoption of improved cultivation technologies have contributed to enhancing productivity and fruit quality in newly established orchards. However,

these positive effects remain uneven across producers, given differences in access to investment capital, irrigation infrastructure, and post-harvest facilities.

The case of peach cultivation highlights both the opportunities and vulnerabilities of the horticultural sector. While modernization efforts supported through public subsidies have the potential to improve efficiency and competitiveness, the sector remains exposed to climate-related risks, market volatility, and structural constraints such as fragmented landholdings and insufficient post-harvest infrastructure. Consequently, the development of peach production underscores the

need for targeted policy interventions aimed at stabilizing incomes, strengthening producer cooperation, and facilitating access to high-value export markets (Iatisin T., 2025).

At the national level, according to National Bureau of Statistics (NBS), (Figure 1), we note that most of the areas are in the southern region of the Republic of Moldova, totaling 765 ha, while the productive area of peach plantations amounts to 670 ha, characterized by a climate favorable for planting and cultivating peaches. The smallest areas are found in Chisinau municipality, around 17 ha of peach.

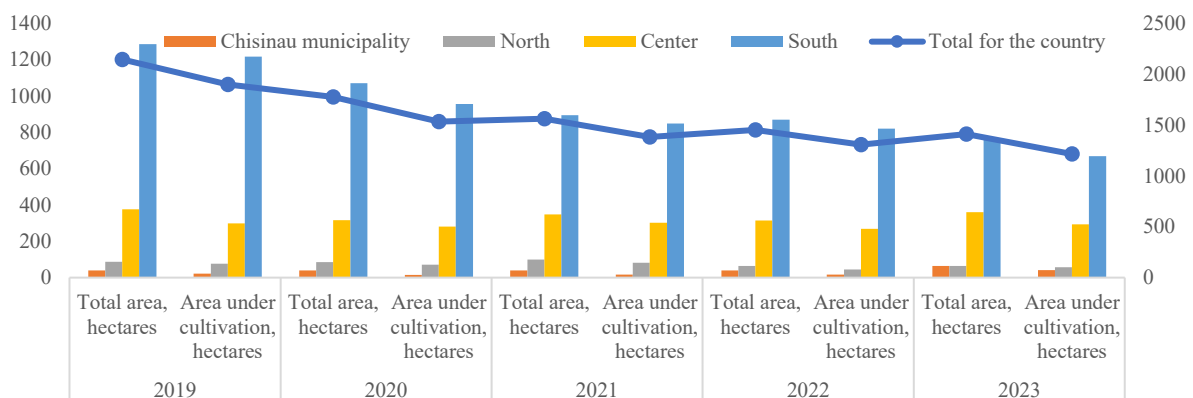


Figure 1 – Total area and global yield of peach plantations in the Republic of Moldova, in the years 2019-2023

(Source: National Bureau of Statistics, 2024).

Therefore, in recent years, the strategic direction of horticulture consists in the efficient exploitation of plantations with high productivity potential, the clearing of those that have been depleted and their consistent replacement with new types with modern varieties and advanced technologies, which ensure early fruiting, high and stable productivity, with quality competitive on both the domestic and foreign markets. Authorities play an important role in the development and modernization of the horticultural sector by attracting investments.

Subsidy mechanisms

Subsidy mechanisms play a central role in shaping investment decisions and production

performance within the horticultural sector. The availability of preferential credit programs co-financed by international partners such as the World Bank, IFAD, the European Investment Bank, the Government of Japan, and the U.S. Compact Program, alongside national support measures implemented through the National Fund for Agricultural and Rural Development, has stimulated producers to invest in advanced technologies and modern production systems.

The analysis of agricultural subsidy policies indicates that the effectiveness of public financial support depends not only on the volume of available funds, but also on their structure, eligibility criteria, and the institutional capacity for implementation. Targeted support for orchard establishment, post-

harvest infrastructure, and technological upgrading has generated positive outcomes; nevertheless, limited access to co-financing and administrative complexity continue to constrain participation, particularly among small and medium-sized producers (Government Decision no. 840 of 18.11.2020). Over the past 3 years, the value of investments in agriculture and rural areas has been continuously increasing. In 2023, the National Fund for the Development of Agriculture and Rural Areas (FNDAMR) was initially set at 1,500 million lei, later increased by 13.3% to 1700 million lei. During the same period, the Agency for Intervention and Payments in Agriculture (AIPA) examined and authorized for payment 7542 applications for financial support received the previous year, with a total value of subsidies granted of approximately 1131.8 million lei (Report, AIPA 2023).

The structure of financial allocations highlights the priority orientation of subsidies towards investments with medium and long-term economic impact. Thus, the largest share of resources was directed towards investments in post-harvest and processing infrastructure, for which 536 applications were authorised, with a total value of 303.0 million lei, representing 26.8% of the total subsidies granted. This financing direction contributes to increasing the added value of agricultural production and reducing post-harvest losses.

Another significant area of support was the subsidisation of the acquisition of agricultural machinery and equipment. In this segment, 1,196 applications were authorised, with a total subsidy value of 145.8 million lei 12% of total subsidies. The value of investments made by agricultural producers amounted to approximately 709.5 million lei, representing 19.0% of the total declared investment value, reflecting a significant leverage effect of public support on private investments. At the same time, subsidies aimed at encouraging investments for the establishment, modernisation, and clearing of perennial plantations, including vineyards and orchards, constituted an important pillar of agricultural policy. By 31 January 2023, AIPA had authorised 528 applications for financial support, with a total subsidy value of 126.5 million lei, equivalent to 11.2% of total subsidies granted.

Overall, during the analysed period, 4023 unique agricultural producers benefited from subsidies, indicating a relatively high level of public fund absorption. However, the results obtained underline the need for continuous optimisation of eligibility criteria and subsidy allocation mechanisms to maximise the economic, social and environmental impact of public support provided to the agricultural sector (Report, AIPA 2023).

Structural constraints

Despite the positive effects of investment and subsidy mechanisms, the horticultural sector continues to face persistent structural constraints that limit its overall competitiveness and resilience. Fragmented land holdings reduce economies of scale and increase production costs, while the shortage of skilled labor and demographic pressures in rural areas further constrain productivity growth. In addition, underdeveloped post-harvest infrastructure and logistical bottlenecks hinder value addition and limit producers' capacity to supply consistent volumes to high-value markets.

The sector also remains highly exposed to climatic variability and market volatility, exacerbating income instability in the absence of comprehensive risk management instruments. These structural challenges underscore the need for an integrated policy approach that combines investment support, effective subsidy mechanisms, and structural reforms aimed at strengthening producer cooperation, improving access to finance, and enhancing institutional capacity. In transition economies, including the Republic of Moldova, agricultural subsidies play a catalytic role in private investment, contributing to the modernization of farms, increased productivity, and the strengthening of farmers' resilience to climatic and economic risks. The focus of subsidies on investments in irrigation, storage, processing infrastructure, and agricultural machinery reflects a paradigm shift from compensatory support to the stimulation of structural development in the sector. In particular, the support provided to the horticultural sector and perennial plantations contributes to the diversification of agricultural production, the increase of added value, and the more efficient

integration of producers into agri-food value chains. At the same time, these investments are associated with positive effects on rural employment and the stability of agricultural incomes. Nevertheless, the analysis of the absorption rate of funds highlights the existence of structural and institutional constraints. These include the unequal level of information available to farmers, the limited capacity of small and medium-sized farms to co-finance eligible investments, and the complexity of administrative procedures. In this context, the quality of the institutional information and communication process becomes a determining factor in access to subsidies, affecting both the distribution of beneficiaries and the efficiency of public fund utilisation (Agenda 2030, 2023).

It is also noted that there is a tendency for subsidies to be concentrated among agricultural holdings with a higher level of capitalisation, which may amplify structural disparities in the agricultural sector. Although this concentration is partially justified by the superior capacity to implement investments, it raises questions regarding the fairness and inclusiveness of support policies. Therefore, a finer calibration of subsidy instruments is needed to ensure a balance between economic efficiency and social cohesion in rural areas. Overall, the analysis demonstrates that agricultural subsidies can generate significant effects on the sustainable development of the agricultural sector only under conditions of a coherent institutional framework, transparent allocation mechanisms, and effective communication with the final beneficiaries. Strengthening administrative capacity, simplifying procedures, and adapting support instruments to the specific characteristics of different categories of producers are essential directions for increasing the economic and social impact of agricultural subsidies in the Republic of Moldova.

In this context, the assessment of horticultural product markets, particularly peaches, acquires a strategic importance for understanding the competitive positioning of domestic producers. The increase in production volumes and exports recorded in recent years is the combined result of farmers' efforts to modernise plantations and improve product quality, as well as state

interventions through subsidy instruments aimed at investments in infrastructure, technology, and irrigation. Nevertheless, efficient access to markets remains dependent on producers' ability to meet increasingly stringent requirements regarding quality, traceability, and continuity of supply.

Competitiveness of the Horticultural Sector

The competitiveness of the horticultural sector in the Republic of Moldova is shaped by a complex interaction of structural, economic, and institutional factors. Despite favorable agro-climatic conditions and a long-standing tradition in fruit production, the sector continues to face constraints that limit its ability to fully exploit comparative advantages and achieve sustainable integration into high-value markets.

From a structural perspective, competitiveness is affected by the fragmentation of agricultural land, the predominance of small-scale producers, and the uneven level of technological adoption. These factors constrain economies of scale, increase production costs, and reduce the capacity of producers to meet the quality, consistency, and traceability requirements of international markets. At the same time, insufficient development of post-harvest infrastructure particularly cold storage, sorting, and packaging facilities limits value addition and weakens the sector's market position (Golban A., 2015). Applying this concept at the microeconomic level allows for the assessment of agricultural enterprise performance and the identification of sources of competitive advantage. For the analysis of the competitiveness of agricultural enterprises in the horticultural sector of the Republic of Moldova, including those specialised in peach production, the *"Five Forces Model that Shapes Competition"* developed by Michael Porter is used (Al-Hiary, Al-Zu'bi and Jabarin, 2010). This analytical framework allows the assessment of market competition intensity by examining the bargaining power of suppliers and buyers, the threat of substitute products, the risk of new entrants, and the degree of rivalry among existing producers. The use of Porter's model

provides a solid methodological basis for identifying the factors that influence the access and positioning of Moldovan horticultural products in

the marketing markets, as well as for formulating policy recommendations aimed at strengthening the competitiveness of the sector.



Figure 2 - Competitive analysis of the horticultural sector based on Porter's Five Forces Model

(Source: Al-Hiary et al., 2010)

The analysis of agricultural enterprises in the horticultural sector through the lens of Michael Porter's five competitive forces highlights that the level of competition in the domestic market of the Republic of Moldova is moderate, without a pronounced orientation towards consumers or producers. In the absence of stable and diversified external markets, this competitive structure can generate increased risks of overproduction, with negative effects on farmers' prices and incomes (Figure 2). The threat of new entrants to the market is relatively low, mainly due to high investment barriers. Starting a business in fruit production requires significant long-term investments in perennial plantations, with extended periods for capital recovery. Unlike the vegetable sector, where production cycles are shorter, including in greenhouse production, the fruit sector involves higher financial risks and requires a higher level of capitalisation. At the same time, new entrants are constrained to comply with increasingly strict standards of quality, packaging and product presentation in order to compete with existing producers on the market.

The bargaining power of consumers is increasing, amid the diversification and sophistication of consumption preferences. Contemporary consumers exhibit increasingly complex demands, focused on quality, authenticity, food safety and nutritional benefits. At the same time, their expectations evolve faster than the current capacity of producers to meet them, a phenomenon amplified by global trends regarding the consumption of functional or "superfoods". This imbalance is accentuated by the relatively low level of knowledge about nutrition, both among consumers and producers (Stratan, Iatisin and Ceban, 2023).

Market access and export orientation play a decisive role in shaping competitiveness. While export diversification has improved in recent years, Moldovan horticultural products remain exposed to external shocks, trade barriers, and geopolitical risks. The limited development of branding and producer organizations further weakens negotiating power along the value chain and reduces the capacity to secure premium prices in foreign markets (Toaca, Iațișin and Colesnicova, 2024).

Exports and European Integration

The geography of horticultural exports from the Republic of Moldova has expanded significantly since 2015, marking a gradual transition from a highly concentrated export model toward a more diversified structure. The growing share of table grapes, plums, and other fruit products reflects producers' increasing capacity to comply with international market requirements and to adapt to changing demand conditions. Nevertheless, export dynamics remain highly volatile, underscoring the sector's vulnerability in the absence of effective

income stabilization and risk management instruments, as highlighted by recent sectoral assessments (Toaca et al., 2024).

The exceptionally high export levels recorded in 2018 both in quantitative terms (6,162.1 tonnes) and in value (USD 2,918.8 thousand) can be attributed to favorable external market conditions and the relatively stable functioning of national support mechanisms at that time. However, the sharp decline observed during 2019–2020 revealed the structural fragility of export-oriented horticultural production and the limited capacity of existing policy instruments to buffer income shocks.

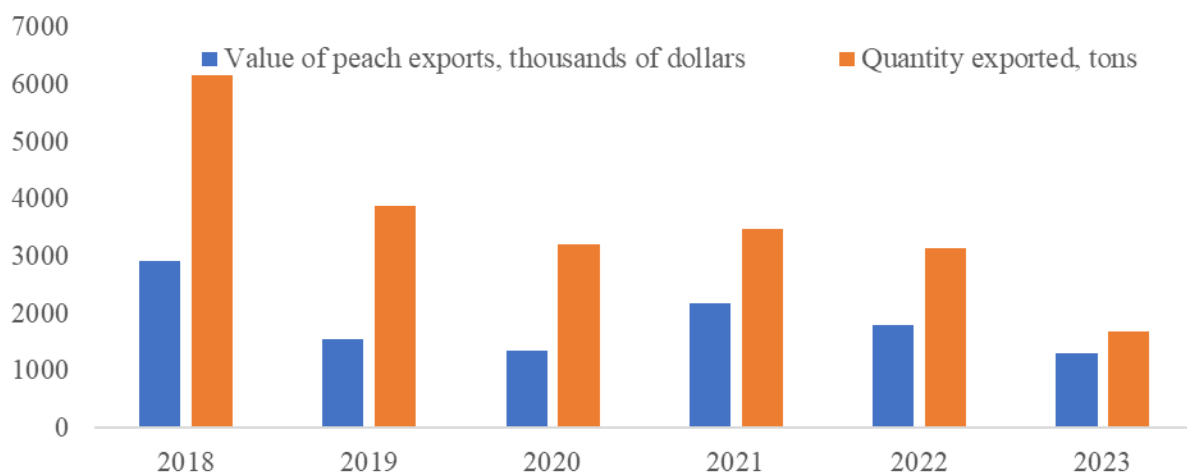


Figure 3. *The evolution of peach exports from the Republic of Moldova, 2018-2023 period*

(Source: data from the UN Comtrade Database)

The trends illustrated in Figure 3 confirm a broader pattern of adaptation and diversification in horticultural exports, while simultaneously revealing pronounced fluctuations in both volumes and values of peach exports. Following the 2018 peak, exports contracted sharply in 2019–2020, partially recovered in 2021, and subsequently experienced renewed downward adjustments. This evolution reflects exposure to multiple risk factors, including adverse climatic events, instability in external markets, and logistical disruptions (Iatisin T., 2025).

Within the framework of the CAP 2023–2027, these developments highlight the relevance of the new delivery model, which emphasizes performance-oriented interventions and greater

subsidiarity in policy design. In particular, CAP Pillar I interventions, focused on income support and resilience, are highly relevant for perennial crops such as peaches. The observed contraction of cultivated areas and yield volatility during unfavorable years suggest that insufficient income support increases producers' exposure to climate- and market-related risks. The introduction of coupled or differentiated income support for perennial fruit crops, aligned with national strategic priorities and CAP conditionality requirements, could contribute to stabilizing farm incomes and encouraging long-term investment in orchard renewal.

At the same time, the enhanced conditionality framework and eco-schemes introduced under CAP

2023–2027 provide additional opportunities to improve both environmental sustainability and economic resilience. Eco-schemes rewarding practices such as sustainable orchard management, efficient water use, soil protection, and biodiversity conservation could support climate adaptation while compensating producers for compliance costs. For peach producers, participation in eco-schemes could strengthen resilience to climate variability and contribute to more stable production outcomes (European Commission, 2024; OECD, 2024).

Equally important are CAP Pillar II interventions under rural development, which remain central to addressing structural constraints. Support for investments in irrigation infrastructure, post-harvest facilities, digital technologies, and orchard modernization directly contributes to productivity gains and quality improvements. Moreover, interventions supporting producer organisations, cooperation, knowledge transfer, and innovation (AKIS) are critical for enhancing bargaining power, achieving economies of scale, and improving access to high-value EU markets. However, the uneven distribution of these benefits indicates the need for improved access to co-financing and stronger institutional capacity at farm level.

Overall, the case of peach cultivation illustrates the complementarity of CAP 2023–2027 instruments, combining Pillar I income support, eco-schemes, and risk management tools with Pillar II investment and cooperation interventions. A coherent policy framework aligned with the CAP 2023–2027 architecture could enhance the resilience, competitiveness, and sustainability of peach production, facilitating the integration of Moldovan horticultural products into European agri-food value chains (European Commission, 2024; OECD, 2024).

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Conclusions

The research confirms the strategic role of the horticultural sector in the economy of the Republic of Moldova and its potential to contribute to sustainable rural development. Technological modernization and subsidy policies have had a positive impact on productivity and economic efficiency; however, structural vulnerabilities persist, particularly with regard to production and export volatility, fragmented production structures, and insufficiently developed post-harvest infrastructure.

Export market diversification, the strengthening of producer cooperation, the development of horticultural branding, and the adaptation of support mechanisms in line with the principles of the Common Agricultural Policy (CAP) represent essential directions for enhancing the competitiveness and resilience of the Moldovan horticultural sector in the medium and long term.

In the context of the European integration process, gradual alignment with the Common Agricultural Policy acquires strategic importance for the future development of the horticultural sector in the Republic of Moldova. The experience of the European Union demonstrates that CAP instruments significantly contribute to income stabilization, the reduction of vulnerabilities arising from climate-related risks and market volatility, and the stimulation of long-term agricultural investments.

The implementation of coherent policies inspired by the CAP would facilitate the integration of Moldovan producers into European value chains, encourage the development of producer organizations, and contribute to strengthening the resilience of the horticultural sector in the face of economic, commercial, and geopolitical shocks.

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Role of Digital Technologies in Green Business Models

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Abstract

The increasing adoption of digital technologies has transformed the way organisations report to sustainable business models. This study presents a bibliometric analysis of research on green business models adopting digital technologies based on 1290 publications retrieved from the Web of Science (WoS) database. The analysis examines publications over time, author keywords, leading authors, institutions, countries, and publication sources. The results indicate a significant growth in research after 2020, with digital transformation, green innovation, sustainability, and artificial intelligence being the dominant research topics. People's Republic of China (PRC) is the leading contributor to the field, and Sustainability is the most productive journal. The study provides an overview of the current research trends highlighting the importance of digital transformation, sustainability, and sustainable business models.

Keywords: digital platforms, digital transformation, green business model, sustainability

Introduction

The increased environmental challenges and rapid technological development have led organisations to design their business models to integrate sustainable practices and digital technologies. Digital platforms allow organisations to collect, analyse, and transmit information more efficiently which leads to better decision-making and improved environmental performance.

This study presents a bibliometric analysis of publications related to the combination of green business models and digital technologies. The objective is to identify the main themes and productive contributors to the field. The following research questions guide this bibliometric analysis:

- What is the evolution in time of publications on green business models and digital technologies?



- Who are the most influential authors, organisations, countries, and publication sources in the researched field?

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- What are the main research themes identified through the keyword analysis?

Literature review

Business models have become an important part of research, and the increased attention that sustainability principles have received in recent years has led to their integration into business models. At the same time, the advance of digital technologies has created new opportunities to help implement sustainable practices.

Understanding the concept of business models is important because it explains how organisations create and deliver value to consumers. Teece (2010) argues that a business model describes how an organisation relates to customer value and that a business model should be combined with a business strategy and innovation to achieve long-term competitive advantage (Teece, 2010).

Business model design has gained a practical approach when Osterwalder and Pigneur (2010) introduced the Business Model Canvas, which is a framework for designing and analysing business models. Their framework follows nine building blocks including key partners, customer segments, value proposition, and key activities. The framework is widely used because it provides a simple and structured way to create and analyse business models (Osterwalder and Pigneur, 2010).

Sustainability has become an organisational objective for more companies and Bocken et al. (2014) examined how business models can contribute to sustainability by proposing sustainable business models that incorporate different archetypes to encourage organisations to reduce their negative environmental impact (Bocken et al., 2014).

Geissdoerfer et al., (2018) argue that sustainability should be integrated into the activities of organisations rather than created as a separate objective for environmental responsibility to become a competitive advantage and a continuous source of innovation. Ludeke-Freund et al. (2018) argue further and present a framework that helps companies identify solutions to achieve their sustainability goals.

The importance of sustainable business models is also confirmed by Nosratabadi et al. (2019) who reviewed the literature and identified key research themes, concluding that there is an interest in integrating a sustainable business model (Nosratabadi et al., 2019). Thus, digital technologies have become an enabler in adopting sustainable business practices. Brenner (2018) argues that digitalisation creates new opportunities to develop and improve the environmental and social performance of organisations (Brenner, 2018).

Broccardo et al. (2023) examined the relationship between digitalisation and sustainable business models concluding that digital technologies can improve resource optimisation and innovation, as well as monitoring and improving sustainability (Broccardo et al., 2023). Similarly, Bencsik et al. (2023) argue that digital technologies help companies improve performance and outcomes of sustainability objectives (Bencsik et al., 2023).

A framework that includes economic, environmental, and social factors and emphasises collaboration between stakeholders shows the importance of data in sustainable business models (Manninen et al., 2023). Digital platforms can act as facilitators for collaboration between stakeholders by implementing accessible interfaces.

Parida et al., (2019) argue that digital technologies can improve competitiveness and help in achieving sustainable goals and Egodawe et al., (2022) show that digital transformation influences innovation and organisational strategies. The literature indicates that sustainable business models and digital technologies are interconnected. To see how these concepts have evolved and what the main research themes are, a bibliometric analysis is carried out.

Research methodology

To identify the evolution and main research themes, a bibliometric analysis was conducted using the Web of Science database. The databases considered are presented in Table 1.

Table 1 – Databases considered for the analysis

Database	Advantages	Limitations
Scopus	Frequently used in bibliometric studies; broad and interdisciplinary coverage.	Harder to use interface; can potentially omit regional or new publications; requires a paid subscription.
Web of Science (WoS)	Frequently used in bibliometric studies; friendly interface; easy to use search tools.	Can potentially omit newer or regional publications; high cost.
Dimensions	Wide coverage of publications; partially free version.	Requires a cost for full access; it can have duplicates because of its wide coverage of publications.
Google Scholar	Wide coverage of documents; it is free; multidisciplinary coverage of different topics.	Harder automated data extraction; limited advance search and filtering tools.
Crossref	Large coverage of publications; regular updates; partially free to use.	Requires data processing skills; potential uneven coverage across different disciplines.

The Web of Science (WoS) database was selected for the following reasons: the database is frequently used in bibliometric studies, access is provided for free for students through the university, and the friendly interface.

The search strategy was developed in two complementary parts that reflect the central theme of the research: green business models and digital technologies. Combining these two dimensions with the *AND* operator ensures that publications that include sustainability-oriented business models and digital technologies are considered.

The search formula used for the bibliometric study was:

TS = (("green business model*" OR "sustainable business model*" OR "green innovation" OR "sustainable innovation" OR "sustainable value creation") AND ("digital platform*" OR "digital transformation" OR "digital technolog*" OR "information system*" OR "environmental data" OR "data collection" OR "data management"))).

The two dimensions of the formula are:

- "green business model*" OR "sustainable business model*" OR "green innovation" OR "sustainable innovation" OR "sustainable value creation" – focuses on the sustainability perspective.
- "digital platform*" OR "digital transformation" OR "digital technolog*" OR "information system*" OR "environmental data" OR "data collection" OR "data management" – focuses on the technological perspective.

The bibliometric study investigates the publications that approach sustainable business models and digital capabilities to provide a comprehensive overview of the research field.

The bibliometric analysis was performed at the end of June 2026, and 1290 results were obtained from the database. VOSviewer and MS Office were the software used to analyse the data extracted and they were selected for their friendly interfaces, their use in dealing with large data sets and their recurrence in bibliometric analyses.

Results and discussion

In Figure 1, the authors will show the total number of publications between 2004 and 2026. Figure presents the annual distribution of studies, and an increase in research can be seen during recent years. The highest number of publications was recorded in 2025 with 404 articles, followed by 2026 with 240 articles, and 2024 with 233 articles. The lower number for the year 2026 is because the analysis is happening during this year. The rapid increase in the number of publications beginning in 2020 reflects that the integration of digital transformation with sustainable business models became a major research topic in recent years.

Table 2 presents the first 10 authors who published the most in the research domain, along with the number of documents they published, their affiliations, and their country.

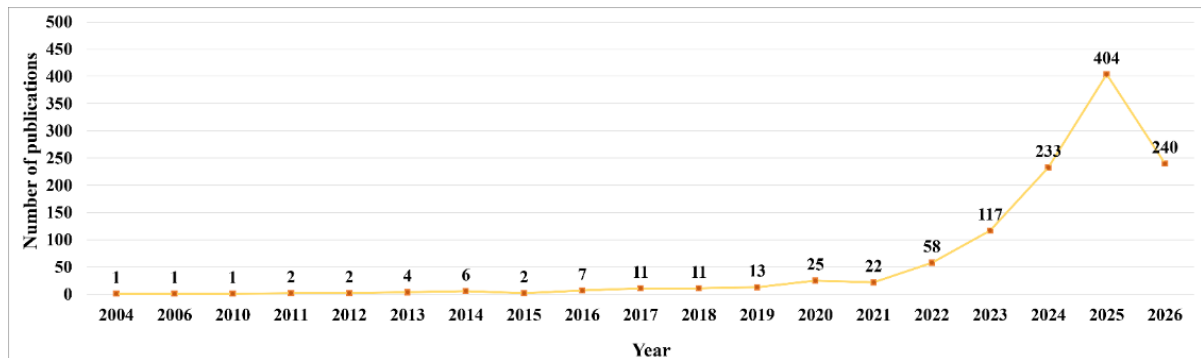


Figure 1 – Publications per year

Table 2 – Authors who have published the most in the field

Authors	Documents	Authors' affiliation	Country
Yi Liu	12	Zhejiang Sci-Tech University	People's Republic of China
Ying Wang	10	University of Texas Rio Grande Valley	United States of America
Shi Yin	10	Hebei Agricultural University	People's Republic of China
Jie Chen	8	Zhejiang Sci-Tech University	People's Republic of China
Nan Li	8	Shanghai Donghai Coll	People's Republic of China
Hao Zhang	8	Zhejiang Shuren University	People's Republic of China
Yu Zhang	8	Chang'an University	People's Republic of China
Yan Li	7	Hebei University of Technology	People's Republic of China
Xin Wang	7	City University of Hong Kong	People's Republic of China
You Chen	6	Shanghai University	People's Republic of China

The analysis identified several authors who published the most, Yi Liu being the most productive author with 12 publications followed by Ying Wang and Shi Yin with 10 publications each. Most of the authors are affiliated with Chinese universities which indicates that People's Republic

of China has a strong concentration of researchers in the domain.

Table 3 presents the first 10 organisations with the most contributions in the field. As can be seen in Table 3, the organisations that have the most documents published are in People's Republic of China.

Table 3 – Organisations' contributions

Organisation	Number of published studies	Country
Central University of Finance and Economics	19	People's Republic of China
Harbin Engineering University	17	People's Republic of China
Xi'An Jiaotong University	17	People's Republic of China
Chinese Academy of Sciences	16	People's Republic of China
Renmin University of China	16	People's Republic of China
Nanjing University of Finance and Economics	15	People's Republic of China
Shandong University of Finance and Economics	15	People's Republic of China
Shandong University	14	People's Republic of China
Shanghai University	14	People's Republic of China
Shenzhen University	14	People's Republic of China

The Central University of Finance and Economics ranks first with 19 documents, followed by Harbin Engineering University and Xi'an Jiaotong University with 17 documents each. The findings indicate that Chinese universities and research institutions play a leading role in research

on digital transformation and sustainable business models.

Table 4 presents the first 10 countries with the highest number of published documents in the researched domain.

Table 4 – *Countries sorted by the number of published articles*

Country	Number of published documents	Citations
People's Republic of China	785	13358
England	64	1445
Italy	64	1764
United States of America	64	1297
Malaysia	51	1233
Saudi Arabia	48	815
Australia	46	1338
India	45	971
South Korea	40	673
Pakistan	39	948

People's Republic of China is the leading contributor with 785 publications, followed by England, Italy, the United States of America, and Malaysia. These findings indicate that People's Republic of China has established a dominant position in the research area.

In Figure 2, the authors will show the geographical distribution of publications. Out of 94 countries, 60 countries have at least 5 documents published in the field. As seen in Figure 2, there are several networks of collaboration between countries.

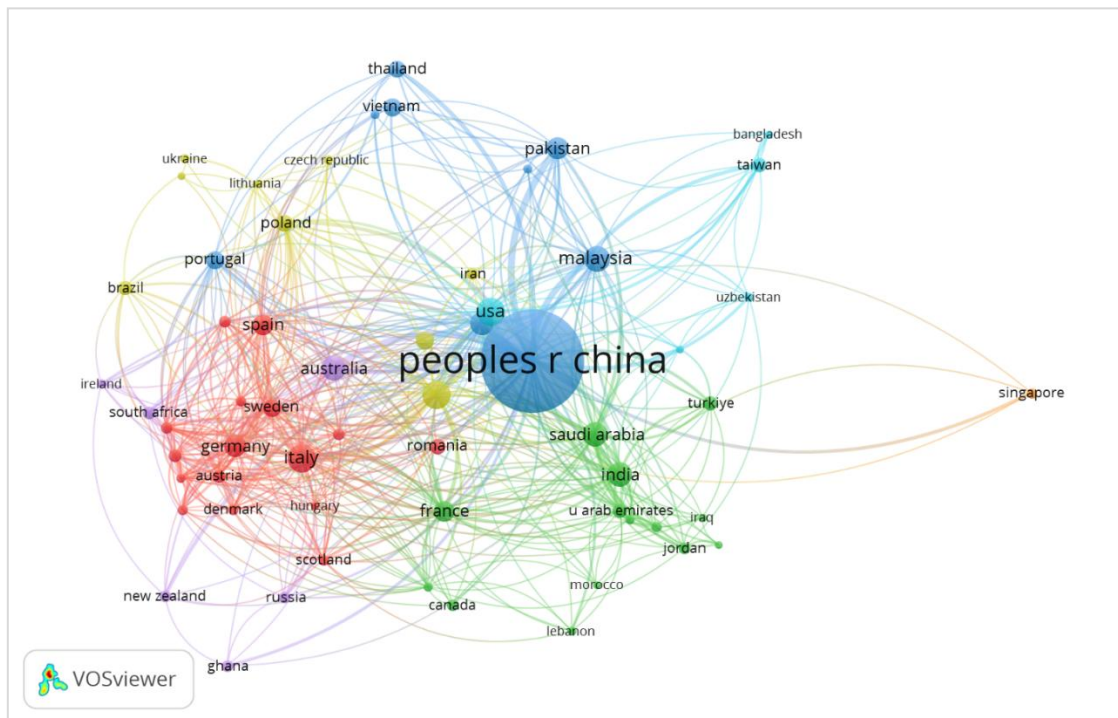


Figure 2 – Geographical distribution of documents

Table 5 shows the first 10 publication sources with the highest number of published studies.

Table 5 – Leading publication sources

Publication source	Number of published documents
Sustainability	201
Finance Research Letters	39
Business Strategy and the Environment	37
International Review of Economics and Finance	35
Systems	35
Journal of Environmental Management	28
Environment Development and Sustainability	23
Frontiers in Environmental Science	22
Journal of Cleaner Production	21
Technological Forecasting and Social Change	19

The analysis indicates that the journal Sustainability published the greatest number of studies, 201, followed by Finance Research Letters with 39 studies, and Business Strategy and the Environment with 37 studies. The variety of publication sources shown in Table 5 demonstrated the multidisciplinary interest in the research area.

A total of 3371 author keywords were identified in the analysis and a threshold for a minimum occurrence of at least five times was applied, leading to 162 keywords being included in the analysis. Table 6 presents the first 10 author keywords that have the highest number of occurrences.

Table 6 – Author keywords with the highest number of occurrences

Nr. crt.	Author keyword	Number of occurrences
1	<i>digital transformation</i>	367
2	<i>green innovation</i>	366
3	<i>sustainability</i>	121
4	<i>sustainable development</i>	69
5	<i>digitalization</i>	63
6	<i>sustainable innovation</i>	60
7	<i>artificial intelligence</i>	58
8	<i>digital technology</i>	46
9	<i>circular economy</i>	43
10	<i>esg performance</i>	43

The results indicate that recent research focuses primarily on the integration of digital technologies with sustainability objectives and highlights the importance of innovation, circular economy practices, and environmental, social and governance (ESG) practices.

To better visualise the authors' keywords and the

networks between them, Figure 3 presents the 162 author keywords that appear in at least 5 articles in the researched field. The analysis generated 11 thematic clusters with keywords such as sustainability, digital transformation, corporate sustainability, digitalisation, artificial intelligence, and ESG performance.

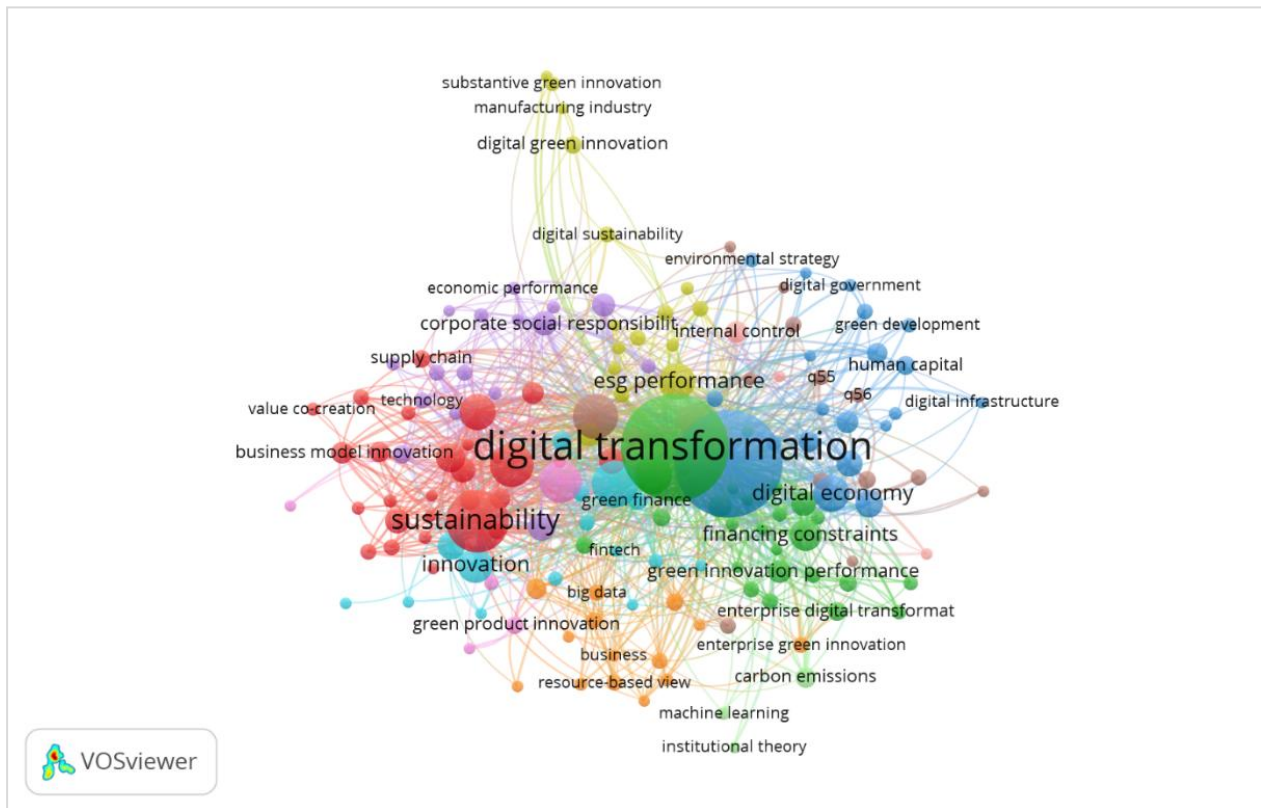


Figure 3 – Author keywords

The diversity in the clusters suggests the multidisciplinary research field and its increasing importance of it.

The bibliometric analysis demonstrates the increasing growth the researched area has had in the last years, highlighting the importance of digital transformation, sustainability, and sustainable business models.

Conclusion

This study provides a bibliometric analysis of research related to green business models enabled by digital technologies. The results indicate a strong increase in scientific publications during recent years, which reflects the importance of the research area. The main directions of the research are centred

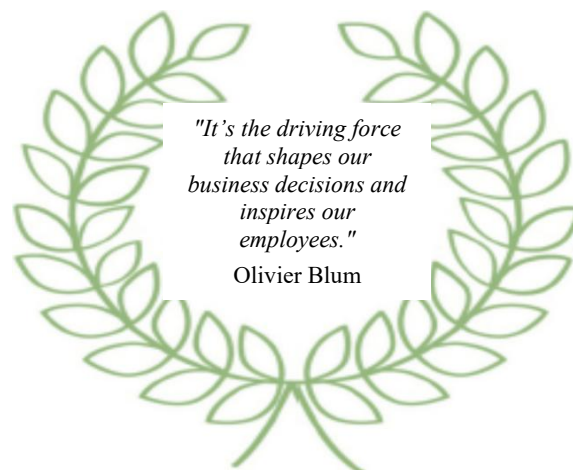
around digital transformation, green innovation, sustainability, artificial intelligence, and ESG practices.

The analysis also indicates that People's Republic of China is the leading contributor in terms of authors, organisations, and countries. The diversity of publication sources shows the multidisciplinary interest in the field, but also the complexity of integrating sustainability objectives with digital technologies.

The study has some limitations, such as being based only on Web of Science publications, and being focused only on the bibliometric indicators. Future research could expand the analysis by including other databases and could examine specific technologies and their role in sustainable business model innovation.

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Position Research Artificial Intelligence in Green Business Model

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Abstract

This paper uses bibliometric analysis to examine how this body of research is organized, which themes have gained attention, and how international collaboration has developed. The data were taken from the Web of Science Core Collection. The search returned 358 records, and 50 peer-reviewed articles published between 2016 and 2026 were retained after filtering, duplicate removal, and relevance screening. The final dataset was analysed in VOSviewer through keyword co-occurrence, temporal overlay, and country co-authorship maps. Six thematic clusters were identified. Artificial intelligence, circular economy, sustainability, sustainable development, and business model innovation occupy central positions in the network, while recent publications give more attention to generative AI, resilience, AI capabilities, digital transformation, and supply-chain applications. The findings also point to the need for more long-term studies, clearer measures of environmental outcomes, and further research on generative AI in green business model change.

Keywords: artificial intelligence, green business model innovation, circular economy

Introduction

Companies are under growing pressure to reduce their environmental impact. Regulation, technological change, and stakeholder expectations have made this issue part of everyday business decisions. As a result, many firms are reconsidering how they use resources, organize production, work with partners, and offer value to customers. Green business model innovation refers to changes in this wider business logic, including the way value is created, delivered, and captured.



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Artificial intelligence has become relevant to this process because it can support forecasting, automation, decision-making, data analysis, and resource planning. Its use may help firms reduce waste, monitor material flows, improve energy use, or develop service-based offers. In some cases, AI also changes the relationship between firms, customers, suppliers, and other partners.

Several studies illustrate these uses. Sjödin et al. (2023) discuss the role of AI capabilities in circular business model innovation within industrial digital servitization. Fallahi et al. (2023) examine AI-based risk assessment in relation to financing circular business models. Jorzik et al. (2024) focus on green technology startups and show how AI can influence value creation, value delivery, and value capture. Wang et al. (2026) connect AI with resource reuse, pollution prevention, and the shift toward circular business models.

The literature has grown across different academic areas. Some authors study environmental performance, while others focus on circular business models, green entrepreneurship, servitization, sustainable innovation, or climate-related value creation. The concepts used in these studies are not always consistent. The level of analysis also varies, since some papers examine individual firms and others discuss wider ecosystems. In several cases, an AI application used in production or operations is described as business model innovation even when the firm's value proposition, partnerships, customer relations, and revenue model remain largely unchanged.

These differences make the field difficult to assess as a whole. It is often unclear where operational improvement ends and business model change begins. A bibliometric approach can help clarify this issue by showing which concepts appear together, which themes have become more visible over time, and which countries are linked through research collaboration.

The present analysis is based on records from the Web of Science Core Collection. The search included terms related to artificial intelligence, business models, circularity, environmental goals, emissions, climate, low-carbon development, and resource efficiency. After the records were filtered, duplicates were removed and relevance was

checked, 50 articles published between 2016 and 2026 remained in the final dataset.

Three research questions guide the study: RQ1: What are the main conceptual themes in research on artificial intelligence and green business model innovation? RQ2: How have these themes changed over time? RQ3: How is international research collaboration distributed across the countries included in the final corpus? By bringing together work from management, sustainability, innovation, entrepreneurship, information systems, and operations research, the paper offers a clearer view of the field. It shows how AI is linked with circular economy, sustainability, and business model change. It also draws attention to the recent growth of research on generative AI, organizational capabilities, and international collaboration.

Literature review

Business model innovation concerns changes in the way an organization creates, delivers, and captures value. It differs from process improvement because it affects the broader logic connecting customers, resources, partners, technologies, and revenue mechanisms. Digital technologies can support this transformation by enabling new products, services, interactions, and organizational structures. However, technological adoption does not automatically represent business model innovation. A company may automate an activity without changing its value proposition or revenue logic (Teece, 2010).

Artificial intelligence extends the possibilities of digital transformation through prediction, classification, optimization, automation, recommendation, and knowledge generation. AI may improve existing operations, but it can also enable data-based services, personalized offerings, platform models, and new relationships among firms and customers. Its strategic contribution therefore depends on whether organizations can integrate AI into their business logic rather than treating it as an isolated technical instrument.

Green business models combine economic value creation with the reduction of environmental impact. Their objectives may include lower resource consumption, reduced emissions, waste prevention, renewable-energy use, product-life

extension, or environmental regeneration. Sustainable business model innovation incorporates environmental and social value into the design of organizational activities, while circular business models emphasize reuse, repair, remanufacturing, recycling, and closed material flows (Bocken et al., 2014; Geissdoerfer et al., 2018).

The transition from a conventional model to a green or circular model may require substantial changes in products, services, ownership, partnerships, and revenue mechanisms. Product-as-a-service arrangements, for example, replace direct product sales with leasing, subscription, or performance-based models. These arrangements change financial flows and require organizations to remain responsible for maintenance, recovery, and residual product value. Consequently, green business model innovation extends beyond environmental efficiency and involves the redesign of value creation, delivery, and capture.

In this study, artificial intelligence refers to computational systems and organizational capabilities that perform functions such as learning, prediction, optimization, automation, recommendation, and natural-language processing.

Green business model innovation refers to the redesign of value creation, value delivery, and value capture in ways that contribute explicitly to environmental objectives. These objectives may include circularity, resource efficiency, emissions reduction, waste prevention, product-life extension, or low-carbon development.

AI-enabled green business model innovation refers to situations in which AI is integrated into the organization's business logic and supports environmentally oriented changes in products, services, processes, partnerships, customer relationships, or revenue mechanisms. This definition excludes situations in which AI is used only as a research method or as a minor operational tool without clear business-model implications.

This distinction is important because AI-enabled sustainability and AI-enabled business model innovation are not identical. An organization may use AI to reduce energy consumption or optimize production while preserving its existing business model. Business model innovation requires more fundamental changes in how environmental and economic value are generated and captured.

A major research direction concerns the use of AI to support circular business models. AI can improve the visibility of products, materials, and resource flows across their life cycles. Predictive systems can estimate product condition, maintenance needs, residual value, or demand for recovered materials. These functions support reuse, repair, remanufacturing, recycling, reverse logistics, and service-based business models.

Sjödín et al. (2023) identify perceptive, predictive, and prescriptive AI capabilities that enable circular business model innovation in industrial digital servitization. These capabilities help firms collect and interpret data, anticipate future conditions, and recommend or automate decisions. They also support new circular value propositions based on optimization services, autonomous solutions, and collaboration with customers and ecosystem partners.

AI can also address financial barriers associated with circular models. Fallahi et al. (2023) show that firms moving from product sales toward product-as-a-service models may experience slower and more uncertain cash flows. Their study demonstrates how AI-based residual-value prediction can support risk assessment and financing decisions, thereby reducing uncertainty for companies and financial institutions.

More recent research connects AI with resource reuse, pollution prevention, and climate-oriented business transformation. Wang et al. (2026) find that AI can support circular business model adoption by improving resource efficiency and enabling new value-creation and value-capture mechanisms. Wu (2026) identifies several pathways through which AI may strengthen circular bioeconomy decarbonization, including resource optimization, product-life extension, intelligent waste management, demand forecasting, and circular business model enablement.

Startups represent an important context for AI-enabled green business model innovation because they often design technological and environmental objectives simultaneously. Unlike established firms, startups may not need to transform deeply embedded structures and can develop data-driven value propositions from the beginning. Jorzik et al. (2024) show how green technology startups use AI across several business-model dimensions to create, deliver, and capture environmental value.

Nevertheless, successful implementation depends on more than the technological solution. AI-enabled green business models frequently require cooperation among technology providers, customers, financial institutions, suppliers, recyclers, and public authorities. Circular systems are therefore often ecosystem-based rather than firm-based. AI can facilitate coordination through forecasting, information sharing, risk assessment, resource matching, and decision support.

Organizational capabilities are also essential. Firms need appropriate data, technological infrastructure, managerial knowledge, employee skills, and the ability to redesign routines and relationships. From a dynamic-capabilities perspective, AI can help organizations identify environmental opportunities, evaluate alternative business models, and reconfigure resources. However, fragmented data, implementation costs, weak interoperability, cybersecurity risks, and limited managerial understanding may prevent firms from converting AI applications into business model transformation.

Although AI may support sustainability, its own environmental effects must also be considered. AI systems require computing infrastructure, electricity, hardware, and data storage. Consequently, an application may reduce resource consumption in one process while generating environmental costs elsewhere. Research on AI for sustainability therefore emphasizes the need to evaluate net environmental effects rather than assuming that every environmentally oriented AI application is sustainable (Nishant et al., 2020).

Governance and human oversight are also important. Organizations must ensure that AI-based decisions remain transparent, ethically controlled, and aligned with credible environmental objectives. Without clear performance indicators and accountability mechanisms, firms may overstate environmental benefits or apply AI only to incremental efficiency improvements while presenting them as business model transformation.

The literature presents three connected perspectives. The first focuses on the technological capabilities of AI, including prediction, automation, optimization, and intelligent decision support. The second examines green and circular

business model configurations, such as digital servitization, product-as-a-service, sustainable platforms, and circular ecosystems. The third emphasizes organizational and ecosystem conditions, including dynamic capabilities, financing, managerial knowledge, partnerships, and governance.

Although these perspectives increasingly overlap, the research field remains fragmented. Studies use different definitions of artificial intelligence, sustainability, circularity, and business model innovation. Some examine operational efficiency, while others focus on organizational transformation or ecosystem-level value creation. As a result, it remains difficult to identify the main intellectual foundations, dominant research themes, influential publications, and emerging areas of the field.

This fragmentation creates the need for a bibliometric analysis. The present study maps the development, conceptual structure, intellectual foundations, and collaboration patterns of research at the intersection of AI, environmental objectives, and business model innovation. It also identifies underdeveloped relationships and future research directions.

Research methodology

This study examines the literature that links artificial intelligence, environmental sustainability, and green business model innovation. Bibliometric analysis was combined with a manual review of the retrieved records. The second step was needed because many papers mentioned AI or sustainability without discussing changes in the business model itself.

The method builds on earlier studies of AI in circular and sustainable business settings. Fallahi et al. (2023), Sjödin et al. (2023), and Jorzik et al. (2024) describe uses of AI in circular value creation, digital servitization, resource planning, environmental decision-making, and changes in value delivery and capture. Their work also shows that this topic crosses several research areas, especially management, technology, sustainability, and innovation.

Three research questions guide the analysis: RQ1: What are the dominant conceptual themes in

research on artificial intelligence and green business model innovation? RQ2: How have these themes evolved over time? RQ3: How is international research collaboration structured across the countries represented in the final corpus?

The first hypothesis expects the literature to form around connected themes such as circular business models, AI-supported value creation, digital transformation, environmental sustainability, and organizational capabilities. For the second question, recent publications are expected to show stronger interest in generative AI, resilience, AI capabilities, digital transformation, and sustainable value creation. The third hypothesis concerns the geographical structure of the field and assumes that international cooperation is concentrated around a small number of countries, with fewer connections among other national research communities.

The bibliographic records came from the Clarivate Web of Science Core Collection. Web of Science provides information on authors, titles, abstracts, keywords, affiliations, references, and citations in a standardized format. The search can also be repeated using the same query, which makes the collection process easier to check.

Only one database was used. This choice kept the metadata in a common format and avoided problems caused by differences in author names, keywords, document types, and duplicate records across platforms. Web of Science also covers the main academic areas relevant to the topic, including business, management, environmental studies, innovation, information systems, and technology.

The search query was built around three groups of terms. The first covered artificial intelligence, the second referred to business models, and the third included environmental and circular objectives. Related expressions were added to each group because authors may describe similar ideas using different terms.

The query used was:

TS=("artificial intelligence" OR "machine learning" OR "deep learning"
OR "generative artificial intelligence" OR "generative AI"
OR "large language model*" OR "AI-enabled" OR "AI-driven" OR "AI-based")
AND ("business model*" OR "business model

innovation")

AND (green OR environmental* OR circular* OR decarboni*
OR "low carbon" OR "low-carbon" OR emission*
OR climate
OR "resource efficiency"))

Data collection ended on June 28, 2026. The first search returned 358 records. Restricting the period to 2016-2026 left 357 publications, and the article filter reduced the set to 247. After selecting English-language records, 244 publications remained. No filter based on research area was applied.

The next stage dealt with duplicate removal and relevance screening. Two duplicates were removed, leaving 242 unique records. Titles and abstracts were then reviewed. This first assessment led to the inclusion of 49 papers, the exclusion of 177, and the classification of 16 records as borderline cases.

The borderline group was read more closely. One paper met the inclusion criteria, while the other 15 were excluded. The final dataset therefore contained 50 articles.

The screening process followed predefined rules. Eligible studies had to be peer-reviewed articles written in English and published between 2016 and 2026. Titles, abstracts, and author keywords were used during the first review. The complete bibliographic record was checked when the available information was unclear.

Three conditions had to be met. First, AI had to appear as a technology, an organizational capability, or a mechanism used in business practice. Second, the study needed a clear environmental objective related to circularity, climate, emissions, decarbonization, low-carbon development, green activity, or resource efficiency. Third, the paper had to discuss business model design, business model innovation, servitization, or changes in value creation, value delivery, or value capture.

Several types of papers were removed from the dataset. These included studies that used AI only as a statistical method and papers in which AI appeared as a small element within a broader set of digital technologies. Studies were also excluded when sustainability had only a minor role or when the discussion focused on operations, procurement, public policy, corporate sustainability, or supply chains without a clear business model dimension.

Duplicate and retracted records were removed as part of the same process.

VOSviewer version 1.6.20 was used to analyse the 50 articles. Three maps were created, each addressing a different part of the study. The keyword map was used to examine the main concepts in the literature. A second map showed the average publication year of the terms, and the country network presented patterns of international co-authorship.

The keyword analysis was based on author-provided terms. Full counting was selected, and a keyword needed at least two occurrences to enter the map. The dataset contained 222 author keywords, of which 27 reached the threshold. “Literature review” was removed because it described a method rather than a research topic. This left 26 terms in the final network.

For the temporal analysis, the same network was displayed as an overlay visualization. Each keyword received a colour according to its average publication year. Blue and purple mark terms connected with earlier papers, whereas green and yellow indicate more recent topics. Using the same keywords in both maps made the two visualizations directly comparable.

The collaboration analysis was based on countries listed in the authors’ affiliations. Fractional counting was applied, and the minimum number of publications per country was set at two. Citation counts were not used as an entry condition. Of the 41 countries found in the records, 21 met the publication threshold. Two were disconnected from the main group, so the final map contains the largest connected component of 19 countries.

The maps were read by considering node size, links, cluster membership, position in the network, and average publication year. Selected papers were also reviewed through their titles, abstracts, keywords, and main arguments. This reading helped explain the patterns visible in the networks.

Results and discussion

The keyword co-occurrence analysis reveals the conceptual structure of the final corpus. The network contains 26 keywords grouped into six clusters, with 81 links and a total link strength of 124. The most prominent terms are “artificial intelligence”, “circular economy”, “sustainability”, and “sustainable development” (Figure 1).

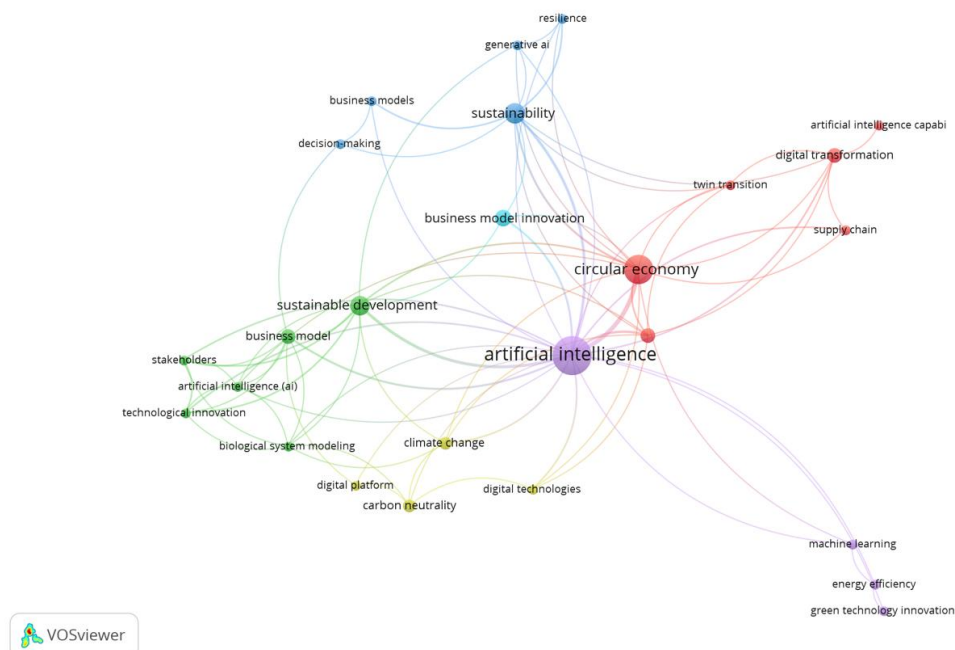


Figure 1 - *The principal research themes in the literature on artificial intelligence and green business model innovation*

Artificial intelligence and circular economy appear close to the centre of Figure 1. Their links extend toward sustainability, sustainable development, business model innovation, and digital transformation. This position suggests that the field has developed around the use of AI in circular activities, environmental performance, and changes in the way firms organize value creation.

The six clusters point to several related lines of research. One brings together AI, circular economy, circular business models, digital transformation, and supply-chain applications. A second cluster connects sustainable development

with business models, stakeholders, and technological innovation. Other parts of the network include generative AI, resilience, climate change, carbon neutrality, energy efficiency, and green technology innovation.

These patterns support the first hypothesis, since the field includes several areas of interest linked through recurring terms such as circularity, sustainability, digital transformation, and business model change, while the overlay visualization adds a time dimension to the keyword network (Figure 2).

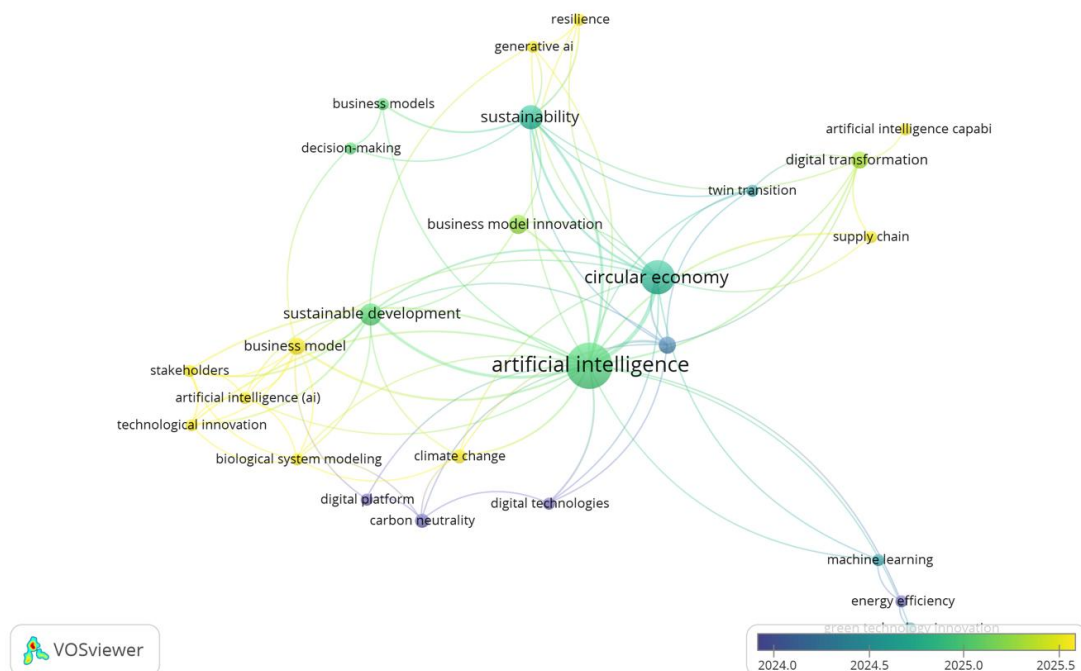


Figure 2 - Temporal evolution of research themes

Digital platforms, carbon neutrality, digital technologies, energy efficiency, and the twin transition are more closely linked with earlier publications. Artificial intelligence, circular economy, sustainability, and business model innovation became more visible during the middle of the period. The most recent part of the map includes generative AI, resilience, AI capabilities, technological innovation, digital transformation, and supply-chain applications.

A change in research interest can be seen across the period. Early papers dealt mainly with digital tools, environmental efficiency, and circularity in broad terms. Later work moved toward the way

firms use AI, the capabilities needed for this use, and the effect on green business models. Generative AI appears within this later stage and continues a line of research already developed around machine learning and digital transformation.

Country co-authorship provides another view of the literature (Figure 3). The corpus includes authors from 41 countries, and 21 of them published at least two papers. The largest connected component contains 19 countries. It is divided into five clusters, with 58 links and a total link strength of 27.50.

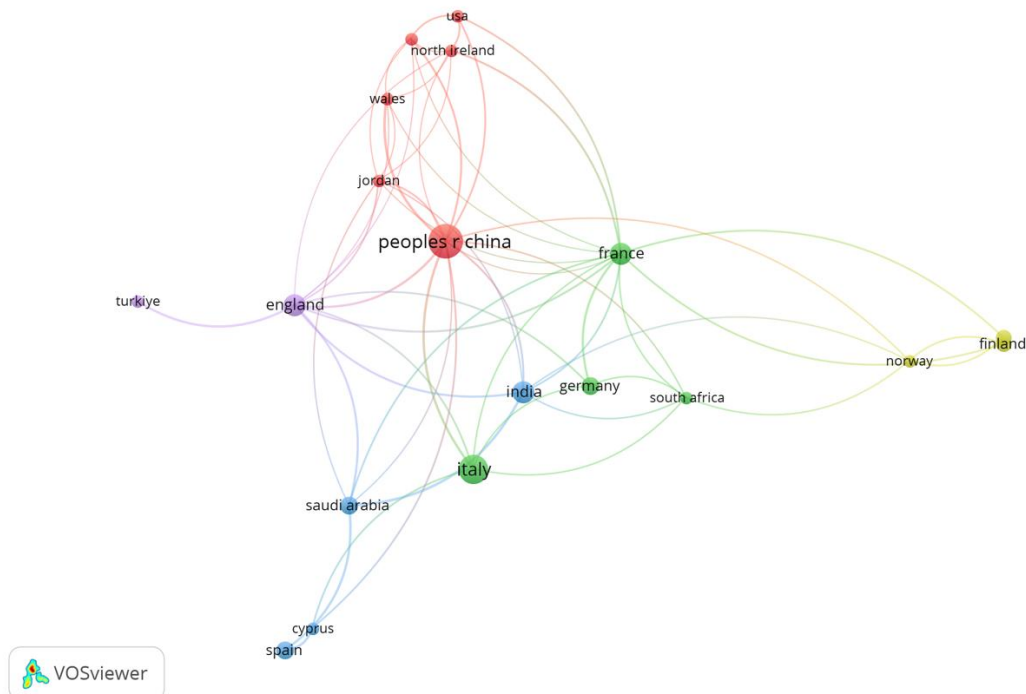


Figure 3 - International collaboration patterns

The People's Republic of China holds the most central position in Figure 3. England, France, Italy, India, Germany, and Saudi Arabia also connect different sections of the map. Finland, Norway, Spain, Cyprus, and Türkiye are located closer to the outer parts of the network.

Research activity is therefore spread across several countries, but the strongest links remain concentrated around a small group of national centres. The third hypothesis is supported by this pattern. International collaboration exists, although its distribution is uneven.

The papers included in the corpus help explain the themes shown in the maps. Sjödin et al. (2023) discuss perceptive, predictive, and prescriptive AI capabilities in circular business model innovation and industrial digital servitization. Fallahi et al. (2023) study the role of residual-value prediction in financing circular business models. Jorzik et al. (2024) focus on green technology startups and describe how AI can influence value creation, delivery, and capture. Wang et al. (2026) connect AI with resource efficiency, reuse, pollution prevention, and circular business model transition.

One issue appears repeatedly across these studies: the boundary between operational improvement and business model innovation. AI can lower energy use, support forecasting, or improve resource planning while the firm keeps the same offer, partner structure, and revenue model. Business model innovation involves changes that reach further into the organization and affect the way value is created, delivered, and captured.

This distinction also matters for managers. AI projects connected with circular goals, cooperation between partners, and measurable environmental results have a clearer link with business model change. Tools used only to improve one process are better treated as operational applications.

Several gaps remain in the literature. Few studies follow AI-supported business model changes over long periods, so their lasting effects are still difficult to assess. Measures for green value creation also vary from one paper to another, and the environmental costs of AI systems receive limited attention.

Generative AI has become more visible in recent publications. Its role in sustainable product development, stakeholder relations, service design, and revenue models still requires further study. Research across a larger number of countries may also show how institutions, infrastructure, regulation, and organizational skills influence the adoption of AI in green business models.

Conclusions

The study traced how research on artificial intelligence and green business model innovation has developed in recent years. The Web of Science Core Collection provided the source material. The first search produced 358 records, and 50 articles remained after filtering, duplicate removal, and relevance screening. These publications were then examined in VOSviewer through keyword co-occurrence, topic evolution, and country collaboration.

Six thematic clusters emerged from the keyword network. Artificial intelligence and circular economy occupy the strongest positions, alongside sustainability, sustainable development, and business model innovation. Their links show that the literature increasingly connects AI with circular practices, environmental value creation, and changes in the way firms design their business models.

The thematic focus has changed over time. Earlier studies were more closely associated with digital platforms, energy efficiency, carbon

neutrality, and digital technologies. Recent work pays more attention to generative AI, resilience, AI capabilities, digital transformation, and supply-chain applications. This pattern suggests that researchers have started to examine the organizational conditions that shape the use of AI in green business model change, with greater interest in capabilities, implementation, and business use.

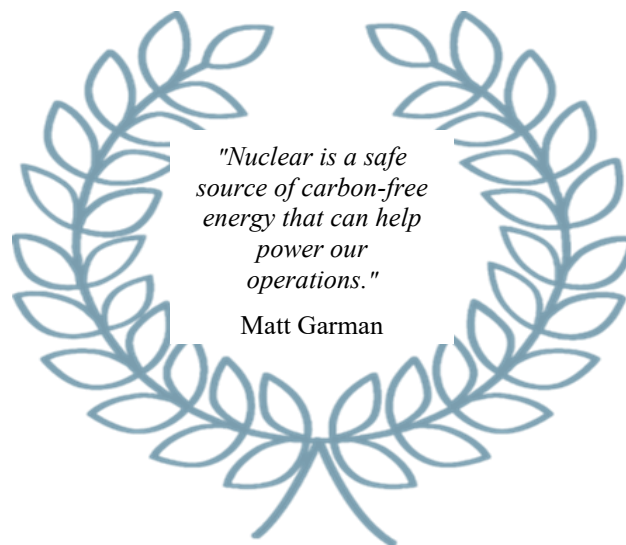
The collaboration map also reveals an uneven international structure. The People's Republic of China occupies the most central position, while England, France, Italy, India, Germany, and Saudi Arabia form important links across the network. Other countries remain less connected. Research activity is therefore spread across several national settings, although the strongest partnerships are still concentrated around a small number of centres.

A clear distinction should be kept between operational improvement and business model innovation. AI can reduce energy use, improve forecasting, or support better resource planning, while the basic business model may remain unchanged. Future studies should examine these changes over longer periods and use clearer measures for both environmental and economic outcomes. More attention is also needed on the environmental cost of AI systems and on the role of generative AI in sustainable products, services, partnerships, and revenue models.

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Digital Identity and Computational Thinking Tools for Traceability and Education in Circular Economy

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Abstract

This article analyzes the Digital Product Passport (DPP) and the European Digital Identity Wallet (EUDI Wallet) as complementary instruments for product traceability and authentication within the circular economy, alongside the role of computational thinking in developing the necessary competencies. The study combines an analysis of the European legislative framework with two practical demonstrations: the digital signing of a Digital Product Passport document via the EUDI Wallet and the design and resolution of an algorithmic problem within a circular economy context utilizing computational thinking. The results confirm the technical feasibility of the existing infrastructure and the direct applicability of computational thinking in circular operations. The study provides practical insights for both management decision-makers and technical specialists.

Keywords: circular economy, digital education, Digital Product Passport, eIDAS 2.0, EUDI Wallet

Introduction

Since its emergence as a theoretical concept, the circular economy has evolved in recent years into a key principle of European industry and environment strategies. According to Ellen MacArthur Foundation (2013), the circular economy is an industrial model which restores and regenerates itself by design and intention. The circular economy is completely opposite to the traditional approach to production and consumption. This direction was supported by the European Commission that published the Circular Economy Action Plan (European Commission, 2020) where circularity would be a core element of the European Green Deal.



However, moving from linear systems to circular production ones is not just about the use of new materials or regulatory innovations. It requires a suitable digital structure that will guarantee traceability and transparency across the full lifecycle of products. Recognizing this need, the European Union introduced the Ecodesign for Sustainable Products Regulation, known as ESPR (Regulation (EU) 2024/1781). Coming into effect in July 2024, the ESPR introduced the Digital Product Passport (DPP) that should be a mandatory instrument for products that are offered for sale in the EU territory. The DPP serves as a digital identity document associated with each item, providing data about the composition, environmental impact, repairability and disposal processes (European Parliament and Council, 2024). Compulsory provisions will be applied to batteries from February 2027, while textiles and other industries will be covered gradually until 2030. Furthermore, international studies conducted recently have highlighted the significance of digitalization in facilitating circularity (GACERE, 2025).

In addition to product tracing, the circular economy also requires another tier of digital trust that guarantees the security of transactions between all actors involved in the value chain, including manufacturers, recyclers, repair service providers, consumers and public administrations. The latest update to the EU's Digital Identity Regulation (Regulation (EU) 2024/1183), which is also referred to as eIDAS 2.0, entered into force on 20 May 2024 and introduced the European Digital Identity Wallet (EUDI Wallet), an application that allows both citizens and companies to store their credentials, prove their identity abroad and sign digitally qualified electronic signatures (European Parliament and Council, 2024b). All member states of the European Union are expected to offer at least one operational wallet by the end of 2026, with mandatory acceptance in regulated private-sector relying parties by the end of 2027. From a circular economy perspective, the EUDI Wallet and its trust services can be used for verifying product origins, authenticating certificates of repairs and refurbishment and executing contracts for secondary materials.

Although digital technology infrastructure may be reliable and robust, it relies heavily on human capabilities that enables designing, implementing and controlling it. As stated by Wing (2006), the concept of computational thinking involves various skills such as problem-solving through abstraction, decomposition, pattern recognition and algorithmic thinking, becoming increasingly relevant to professionals regardless of their field of expertise. The above view has been supported by the Digital Education Action Plan 2021-2027 (European Commission, 2021), which emphasizes the importance of teaching computational thinking with educational curricula. Given the fact that only 27.7% of people in Romania have basic digital skills, compared to the EU average of 55.6 % (European Commission, 2024), the gap between regulatory ambition and workforce readiness represents a significant barrier to circular economy implementation. The process of managing the Digital Product Passport or performing transactions using an EUDI Wallet is not just a technical exercise, but an algorithmic one, which requires the user to understand the logic behind the operation of data flow and validation.

This paper analyzes the relationship between digital trust infrastructure and digital education as two connected elements that contribute to transformation into the circular economy model. The research is based on two main perspectives: the regulatory framework of the Digital Product Passport and EUDI Wallet infrastructure and the role of computational thinking in building digital skills according to circular economy requirements. The theoretical discussions are supplemented by illustrative examples of practical applications obtained from the professional experience of the author within the electronic trust services and algorithmic education.

Theoretical framework

The theoretical base of this study consists of three inter-related domains: circular economy theory, digital trust infrastructure and computational thinking as an educational paradigm. Together, these domains act as strategic enablers of organizational resilience, which refers to an institution's capacity to anticipate, prepare for, and adapt to disruptions.

The concept of circular economy has been widely discussed in scholarly discourse following the work of Geissdoerfer et al. (2017) which distinguished between the two concepts and explained that while sustainability included many environmental, economic and societal factors, the circular economy focuses specifically on closing material loops and minimizing resource leakage. Policy implementation is exemplified by the European Green Deal and its Action Plan for a Circular Economy that mandates product-level transparency using digital passports, including the Digital Product Passport (European Commission, 2020).

The second theoretical element is digital trust infrastructure. The ability to authenticate identity, to verify credentials and to digitally sign a transaction becomes vital for implementing the principles of the circular economy. Schwalm, Albrecht and Alamillo (2022) examined challenges and opportunities of eIDAS 2.0 and highlighted the importance of establishing user-centric identity models based on creating European Digital Identity Wallets whereby the control of the users' data is transferred from centralized institutions to the users themselves. The EUDI Wallet was established under Regulation (EU) 2024/1183 as an instrument for storing credentials, cross-border authentication and signing qualified electronic signatures (European Parliament and Council, 2024b).

Finally, the last pillar of the framework is computational thinking, a widely applicable problem-solving approach that is based on abstraction, decomposition and algorithmic reasoning. As Grover and Pea (2013) pointed out, it must be considered as essential literacy along with reading and writing. However, in the context of the circular economy and its need for interacting with digital passports, trust services and other types of data verification, it transcends being a mere technical skill and instead evolves into a critical competency required for professionals to navigate complex circular systems.

By connecting digital innovation, trust infrastructure and algorithmic education, organizations can transition from reactive management to proactive governance and long-term performance, achieving the strategic

flexibility required for a sustainable modern economy.

Digital trust infrastructure

Just as every European citizen possesses an identity card for official identification, every physical product sold within the European Union will be linked to a digital passport, accessible via a QR code or a unique identifier. This instrument is the Digital Product Passport (DPP), a digital container based on decentralized architecture. In this model, data is not stored in a centralized database but is instead distributed among various stakeholders across the supply chain. The mandatory information within the DPP comprises the unique identifier, manufacturer details, material composition, carbon footprint, recycling data, and repair instructions. Furthermore, access for different stakeholders is governed by the "need-to-know" principle. The first mandatory implementation of the DPP will target batteries under Regulation (EU) 2023/1542, set to become applicable on 18 February 2027. Consequently, any electric vehicle (EV) or industrial battery with a capacity exceeding 2 kWh sold in the EU must feature a digital passport; this requirement will be phased in for other sectors, such as textiles, electronics, and furniture, by 2030.

The Digital Product Passport (DPP) represents a highly innovative development within the digital landscape. However, it cannot function in isolation, as its efficacy depends on verifying the provenance and reliability of the data provided. This is where the European Digital Identity (EUDI) Wallet becomes essential, enabling economic operators to digitally sign the declaration of conformity within the DPP, thereby ensuring data authenticity, integrity, and non-repudiation. Furthermore, the majority of operations undertaken by economic actors will require a verifiable digital identity and a qualified electronic signature (QES). For instance, such actions include the issuance of verifiable repair certificates by authorized providers or the validation of recycling compliance by certified recyclers. The EUDI Wallet provides these precise identification mechanisms in full compliance with the eIDAS 2.0 Regulation.

The typical lifecycle of a product (such as a battery) within the circular economy framework will unfold as follows:

- **Production:** When a manufacturer intends to place a battery on the market, they generate a Digital Product Passport (DPP) and input the relevant technical data, subsequently authenticating the record with a qualified electronic signature (QES);
- **Consumption:** Upon reaching the end-user, the consumer scans the associated QR code to verify the product's identity and provenance;
- **Maintenance and Repair:** In the event of a malfunction, the product is transferred to a repair

center. To perform the service, the technician authenticates their credentials via the EUDI Wallet and appends a verified repair certificate to the DPP;

- **End-of-Life:** At the conclusion of the product's lifecycle, the recycler accesses the DPP to ascertain the exact chemical composition, ensuring that the recycling process adheres to specific environmental and safety standards.

At every stage of this cycle, the identity of the involved stakeholder is verified, and all data transactions are digitally secured through the EUDI Wallet infrastructure.

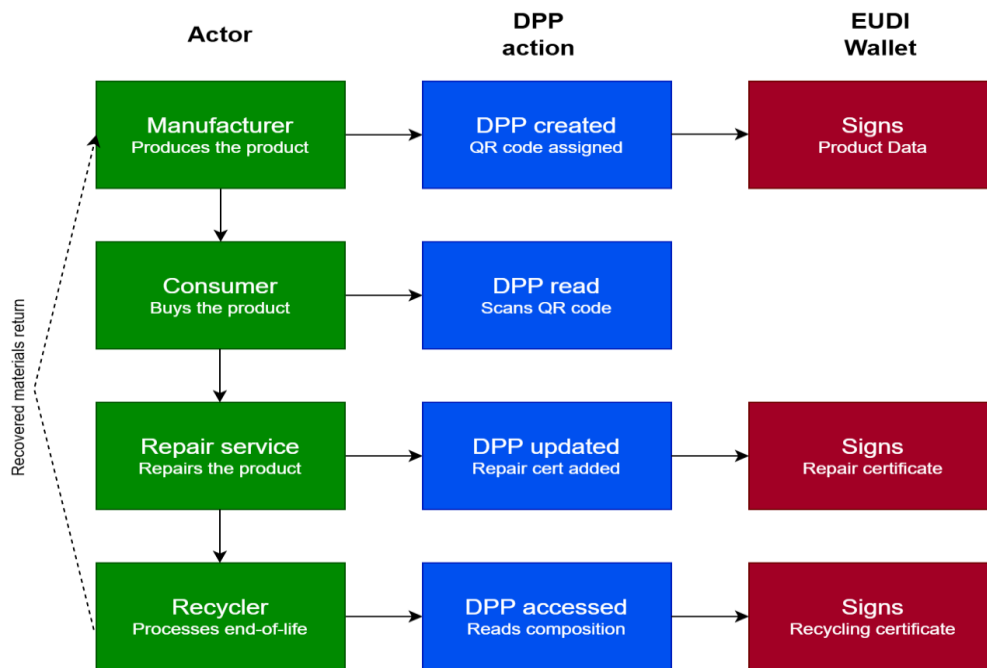


Figure 1 – DPP and EUDI Wallet in the circular product lifecycle

Nevertheless, this robust infrastructure, thoughtfully designed by the European Union, faces several significant implementation challenges. These include cross-border interoperability between disparate DPP systems, the adoption of the EUDI Wallet by organizations with nascent digital frameworks, and the ongoing requirement for data standardization, an effort currently being addressed by the European Committee for Standardization (CEN). Most

crucially, however, the substantial digital skills gap and the precarious state of digital education represent a primary bottleneck, which this article intends to examine.

Digital education

Although the European model is well-defined by numerous technical details that will facilitate the implementation process, this infrastructure will

be futile without specialists who possess the expertise to operate it. Even the most sophisticated Digital Product Passport or the most secure EUDI Wallet cannot resolve the human factor. If a factory operator fails to grasp the underlying logic of a data flow, the system will remain non-functional. While the EU average for individuals possessing basic digital skills is 55.6%, certain member states face a critical deficiency in this area. In Romania, for instance, this figure is only 27.7%. This is a point of significant concern as products and their associated data must circulate seamlessly throughout the European single market. Consequently, this does not represent a purely technological hurdle; it is, in fact, a fundamental management challenge. Organizations will be unable to successfully transition to a circular economy model without a workforce proficient in algorithmic thinking.

What does the concept of computational thinking actually entail? Contrary to common perception, computational thinking is not synonymous with programming proficiency. Instead, algorithmic thinking involves decomposing complex problems into manageable steps, identifying patterns, abstracting irrelevant details, and constructing systematic solutions based on pertinent data. This represents the precise cognitive requirement for an operator when utilizing and managing a Digital Product Passport (DPP). In fact, verifying input data, validating signatures, confirming transactions, and updating records are all actions that can be defined as an algorithm.

In Table 1 are the core principles of computational thinking map onto real-world circular economy operations.

Table 1 - Mapping computational thinking to circular economy operations

Computational thinking component	Circular economy operation	Example
Decomposition	The breakdown of a product into its recyclable components	Each component has its own distinct data set within the Digital Product Passport (DPP)
Pattern recognition	Identifying return or repair trends within DPP data	Pinpointing a specific battery model that exhibits a high frequency of failures
Abstraction	The filtering of relevant DPP data for specific stakeholders	While a manufacturer requires comprehensive data access, a consumer only views information pertinent to usage, and a recycler focuses exclusively on the material composition
Algorithmic Reasoning	The step-by-step execution of a verification workflow that functions as an algorithm	The sequence of scanning a QR code, followed by signature verification, certificate validation, and finally, the update of the product's status

The European Digital Competence Framework, DigComp 2.2 (Vuorikari et al., 2022), defines five distinct areas of digital competence. The third area, "Digital Content Creation," explicitly includes computational thinking as a sub-category under "3.4 Programming." This competency is defined as the ability to apply programming techniques and computational thinking to provide instructions to a digital system. The official recognition of this link by the European Union signifies that algorithmic

thinking is evolving into a requisite competency for all citizens, rather than being restricted to specialists. Competitive programming platforms, through their algorithmic problem-solving exercises, represent a direct and practical method for developing these competencies. The "Results" section will demonstrate how such exercises are applied within the specific context of the circular economy.

Research methodology

This study employs a conceptual and analytical approach to explore the interplay between digital trust infrastructure, digital education, and the circular economy. The integration of the EUDI Wallet with the Digital Product Passport (DPP) represents a nascent development currently in the implementation phase, characterized by significant technical and regulatory uncertainties. Given the scarcity of literature explicitly linking these two legislative-technical frameworks, a qualitative approach was necessitated, combining rigorous theoretical analysis with practical demonstrations. The methodology comprises two primary components:

Literature and Regulatory Analysis. This component involved an extensive review of academic literature and the European legislative framework. Primary sources included peer-reviewed journals and key European Union regulations, specifically the ESPR (Regulation 2024/1781), the eIDAS 2.0 (Regulation 2024/1183), and the Battery Regulation (Regulation 2023/1542), as well as European Commission reports on digital competencies, such as the DigComp 2.2 framework. This analysis facilitated the identification of a distinct convergence between the three primary domains under investigation.

Practical Demonstrations. Two practical demonstrations were conducted to substantiate the theoretical frameworks presented in this study. The first demonstration involves the digital signing of a simulated Digital Product Passport (DPP) using the EUDI Wallet mobile application within an Android environment, integrated with a remote Qualified Electronic Signature (QES) service in compliance with the CSC v2.2.0 standard (ETSI TS 119 432). The objective of this test is to validate the technical feasibility of utilizing the EUDI Wallet for data authentication within circular economy workflows. The second demonstration entails the design of an algorithmic problem set within a circular economy context, intended to showcase the practical application of computational thinking in circular operations. This problem is presented alongside its

formal statement, a programmatic solution, and an algorithmic complexity analysis.

Results and discussion

This section presents the results of the two practical demonstrations described in the methodology: the digital signing of a simulated Digital Product Passport (DPP) via the EUDI Wallet and an algorithmic problem based on a practical circular economy scenario.

Practical Demonstration 1: Digital Signing of a Simulated DPP via the EUDI Wallet

To validate the feasibility of using the EUDI Wallet within the context of the circular economy, a practical demonstration was conducted involving the digital signing of a PDF document simulating the structure of a Digital Product Passport. The document contains structured data for a fictional electric vehicle battery, in accordance with the requirements of Regulation (EU) 2023/1542: product identification (unique identifier, model, batch, GTIN), information on the economic operator, material composition with recyclability indicators, carbon footprint, performance and durability, and end-of-life recycling information.

The document was signed electronically using the official EUDI Wallet application (publicly available) on an Android device connected to a remote electronic signature service (Remote Signing Service) that signs document hashes according to the CSC (Cloud Signature Consortium v2.2.0) standard. The signing workflow followed three stages, illustrated in Figure 2: document selection, connection to the remote signing service, and selection of the digital certificate associated with the signer's identity.

The resulting signature was successfully validated, confirming the integrity of the document and the authenticity of the signer (Figure 3). The certificate used for this signature was a test certificate; in a production scenario, a qualified digital certificate (Qualified Electronic Signature) would be required to ensure full legal validity under eIDAS 2.0. However, the technical workflow is identical regardless of the type of certificate used.

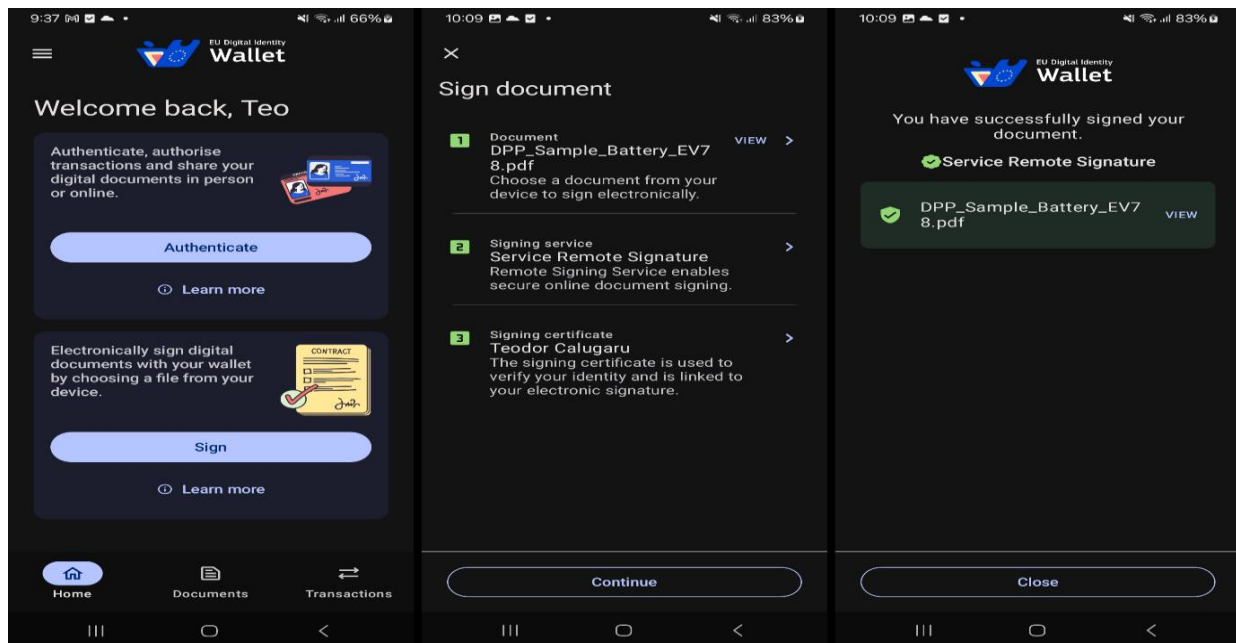


Figure 2 - EUDI Wallet signing flow

DIGITAL PRODUCT PASSPORT

Regulation (EU) 2024/1781 — Ecodesign for Sustainable Products (ESPR)
Regulation (EU) 2023/1542 — Batteries and Waste Batteries

1. Product identification

Unique product identifier	DPP-EU-2026-BAT-00472819
Product type	Lithium-ion battery — Electric vehicle (EV)
Model identifier	VOLTERRA EV-78 Pro
Batch number	BATCH-2026-Q1-0042
Manufacturing date	2026-01-15
Manufacturing location	Gigafactory Wrocław, Poland
GTIN (Global Trade Item Number)	5901234567890

2. Economic operator information

Manufacturer name	EuroCell Energy GmbH
Manufacturer address	Industriestrasse 42, 80331 Munich, Germany
EU VAT number	DE-298745123
Authorized representative	EuroCell Compliance BV, Rotterdam, NL

Signature validity is unknown:
Source of Trust obtained from European Union Trusted Lists (EUTL).
Document has not been modified since this signature was applied
Signature is valid, but revocation of the signer's identity could not be
Signing time is from the clock on the signer's computer.

> Signature Details
Last Checked: 2026.04.14 11:34:28 +03'00'
Field: Signature (invisible signature)
[Click to view this version](#)

Figure 3 – Signed DPP with verified signature

Practical Demonstration 2: Algorithmic Problem for Circular Economy

To demonstrate the applicability of computational thinking within the context of the circular economy, an algorithmic problem titled

"DPP Classification for Recycling" was designed and published on the competitive programming educational platform The Programmers Pack (Figure 4).

101. DPP Classification for Recycling

Easy

Algorithmic thinking and fundamentals

★ 100

STATEMENT

Scenario

The European Union has introduced, through the ESPR regulation (2024/1781), the **Digital Product Passport (DPP)**, a mandatory electronic document that accompanies every product sold on the European market. The DPP contains structured information about the product's composition, including the **list of component materials** and the **weight of each material**, along with a label indicating whether the material is **recyclable** or **non-recyclable**.

A recycling center in Romania receives products daily for processing. For each product, the center consults the DPP and must decide whether the product can be accepted for recycling or must be redirected. The rule is simple, but strict:

- Calculate the **total weight of recyclable materials** in the product;
- Calculate the **total weight of the product** (the sum of all materials);
- Determine the **recyclability percentage**:

$$P = \frac{\text{weight of recyclable materials}}{\text{total weight}} \times 100$$

- If $P \geq T$ (where T is the minimum threshold imposed by the center), the product is classified as **RECYCLABLE**;
- Otherwise, the product is classified as **NON-RECYCLABLE**.

Figure 4 - Problem statement: DPP Recycling Classification

The logic of the problem is as follows: a recycling center receives N products for processing, each with an associated Digital Product Passport containing product information, such as a list of component materials and the weight of each material. Based on this data, the recycling center must determine whether the product is acceptable for recycling or should be redirected. To accomplish this, the percentage of recyclable material relative to the total weight must be calculated; if this percentage exceeds a minimum threshold T (established by the recycling center), the product is classified as **RECYCLABLE**, otherwise as **NON-RECYCLABLE**. Finally, the total count of products from N classified as recyclable is displayed. The algorithmic solution

has a complexity of $O(N \times M)$, where N is the number of products and M is the average number of materials per product. The solution was successfully validated against all 25 platform tests, achieving a maximum score of 100/100 points (Figure 5).

The problem directly tests the four components of computational thinking identified in the study's theoretical framework: breaking down the problem into sub-problems per product (decomposition), identifying the repetitive calculation pattern for each product (pattern recognition), filtering relevant information, specifically the weights of materials marked as recyclable (abstraction), and the step-by-step execution of the classification algorithm (algorithmic reasoning).

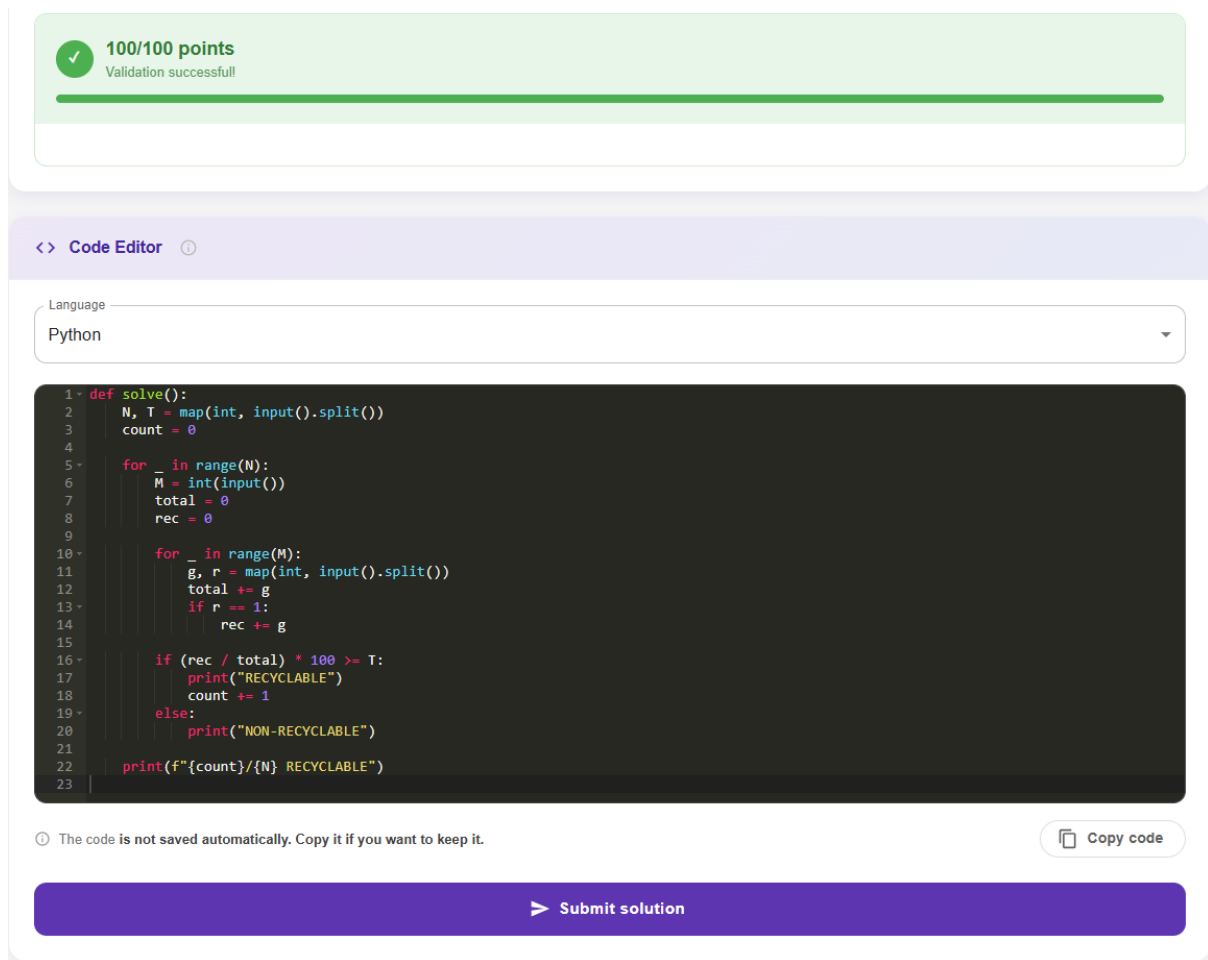


Figure 5 - Validated solution of the problem

Conclusion

This work examined the intersection of digital trust infrastructure and digital education as two foundational components supporting the transition to the circular economy. Initially, an analysis of the legislative and technical framework of the Digital Product Passport and EUDI Wallet was performed; subsequently, the role of computational thinking in developing the digital skills necessary to interact with these components was exemplified, concluding with a practical demonstration of these concepts.

The main findings of the study are as follows. First, the initial practical demonstration highlighted that the technical details regarding the

implementation of the new infrastructure mandated by the European Union are nearly finalized and easily integrated. The format of a Digital Product Passport is already established and was simulated via a PDF document. Furthermore, the successful digital signing of the document through the EUDI Wallet mobile application and a remote signing service demonstrates that the technical infrastructure required for data authentication in the circular economy is already operational. The remote signing workflow enables economic actors to digitally sign data associated with products without physical contact with a cryptographic device, thereby facilitating large-scale adoption. Second, the algorithmic problem designed for The Programmers Pack platform demonstrated that computational thinking can be applied directly to

circular economy operations, and its four components are concretely present in the product classification process based on DPP data. By solving this problem, students demonstrate the competencies required for computational thinking, which is a crucial skill that economic agents must acquire. Third, the significant gap in digital skills within Romania and other European Union member states underscores the urgency of integrating computational thinking into educational curricula, in accordance with the recommendations of the DigiComp 2.2 framework.

The study is subject to several limitations. The signing of the document using the EUDI Wallet was performed with a test certificate rather than a qualified certificate. Although the workflow is

identical, a qualified certificate is required for a real production environment. Additionally, the algorithmic problem has not yet been evaluated on a user group; rather, it was presented as an educational proposal. Future research could empirically evaluate the impact of algorithmic exercises within a circular economy context on the development of computational competencies, as well as test the complete DPP-EUDI Wallet workflow in a production environment with qualified certificates.

The findings of this study are intended for both management decision-makers, who must understand the practical implications of new European regulations, and technical specialists responsible for implementing these systems.

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The Role of Higher Education in Developing Competences for Green Business Models

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Abstract

Higher education institutions play a crucial role in preparing future professionals capable of designing, implementing, and managing such business models by developing the knowledge, skills, and attitudes required for the green transition. Among the approaches supporting Green Business Models, the circular economy provides practical principles for reducing resource consumption, extending product life cycles, and promoting resource efficiency. This paper qualitatively analyzes the relationship between Green Business Models, circular economy principles, and higher education by reviewing the relevant literature and the European policy framework. Based on this analysis, the study identifies the general and specific competencies that higher education institutions should foster through their curricula to prepare students for the implementation of Green Business Models and the transition towards a circular economy.

Keywords: circular economy, competence, green business, higher education

Introduction

Green business models are designed to integrate the principles of sustainable development into all of an organization's activities, with the aim of using resources efficiently, reducing negative environmental impacts, and assuming social responsibility. These models are based on the implementation of sustainable practices and strategies, such as the use of renewable energy sources, the application of circular economy principles, and the development of products designed in accordance with eco-design requirements (Shah, 2025).

In the context of green entrepreneurship, the circular economy is a business model that combines



economic objectives with environmental responsibility. By promoting the efficient use of resources, reducing waste generation, reusing and recycling materials, and extending the lifespan of products, this model contributes both to improving organizations' economic performance and to reducing their environmental impact. Thus, the circular economy supports the development of sustainable businesses capable of creating long-term value for the organization, society, and the environment.

The literature highlights the essential role of higher education institutions in promoting green entrepreneurship. Universities contribute to the development of the skills needed to launch and manage sustainable businesses, providing students with the knowledge and abilities required to integrate environmental principles into entrepreneurial activities. Furthermore, through educational programs, mentoring activities, and other forms of entrepreneurial support, they positively influence students' attitudes and behaviors toward practices specific to green entrepreneurship (Nguyen et al., 2025).

The purpose of this paper is to examine the relationship between Green Business Models, circular economy principles, and higher education in order to identify the competencies required to prepare future professionals for the green transition. The specific objectives are: (i) to outline the theoretical framework of Green Business Models based on the relevant literature, with particular emphasis on the circular economy as one of their main operational approaches; (ii) to examine the role of higher education institutions in developing the competencies required for the implementation of Green Business Models; and (iii) to define the key competencies that can support curriculum development for the green transition.

Conceptual foundations of Green Business Models

The business environment has undergone changes in recent years, particularly from an environmental perspective, as entrepreneurs have integrated sustainability initiatives into their

business models. On the one hand, there are internal reasons (such as ethical business conduct, competitiveness, etc.) and external reasons (such as government regulations and other stakeholders' demands). The adoption of eco-friendly practices affects the entire organization, influencing: decision-making and risk management, employee engagement, the level of innovation, the use of new technologies, as well as marketing and communication activities (Hasan et. al., 2019).

An increasing number of organizations are integrating greening strategies into their operations, adopting sustainable business practices, and developing management models oriented toward sustainable development. In this way, they can benefit from the economic, social, and environmental advantages these practices offer (Paul et al., 2014). Implementing these practices helps stabilize the interaction between industry and the environment, as well as the relationship between business models, industrial activities, and the principles of sustainability (Nair and Paulose, 2014).

A green business can be defined as one that operates guided by eco-responsible conduct, uses green resources, and carries out activities in a way that minimizes negative environmental impacts as much as possible.

In academic and policy-oriented literature, the concept of a green business model is often used alongside the concepts of a sustainable business model and a circular business model, or as a close counterpart to them. A practical guide hosted by the Green Policy Platform defines a *green business model as one through which a company creates, delivers, and captures environmental, economic, and social value* (Green Policy Platform, 2018). This definition is important because it avoids reducing the concept of "green" to mere environmental compliance or so-called eco-efficiency. Instead, it frames eco-businesses as a systemic configuration in which ecological value is embedded in the organization's underlying logic. In recent research on innovation in green business models, the concept is operationalized as the modification of at least one dimension of the business model, so that sustainability becomes part of the model itself, rather than an external add-on.

Among the most important models associated with green business are the Business Model Canvas (BMC), the circular economy, the lean-green model, the greentech model, renewable energy models, and the model based on the Triple Bottom Line (TBL) principle.

(1) The Business Model Canvas (BMC) is a strategic management framework used to describe how organizations create, deliver, and capture value. The model comprises nine interconnected building blocks covering customer-related aspects, value creation processes, infrastructure, and financial performance. These elements include customer segments, value propositions, channels, customer relationships, revenue streams, key resources, key activities, key partnerships, and cost structure. Together, they provide a comprehensive framework for analyzing and designing business models (Aini, 2025).

(2) The circular economy model is based on reintegrating previously used raw materials into the production process through reuse and recycling.

(3) The lean-green model supports the idea of eliminating waste and optimizing processes while minimizing environmental impact.

(4) The greentech model addresses two dimensions: business model archetypes (which illustrate how sustainable value is created and delivered) and technological entrepreneurship activities (which illustrate how green technologies become market solutions).

(5) The triple bottom line model promotes the strategic and transparent integration of the three dimensions of sustainable development—economic, social, and environmental—into organizational practices, with the aim of improving performance (Solevik, Torgersen and Andersson, 2022).

Although green business models encompass a wide range of sustainability-oriented strategies, this paper focuses on the circular economy, as it represents one of the most comprehensive operational approaches for translating sustainability principles into business practice. The circular economy provides organizations with concrete mechanisms for redesigning value creation, value delivery, and value capture through resource efficiency, extended product lifecycles, reuse, and recycling.

Circular Economy as a Foundation of Green Business Models

The circular economy is an evolving concept that has attracted significant interest from organizations, the business community, and the scientific community in recent years. The circular economy is based on three key principles, established right from the initial design phase:

- preventing waste generation and pollution
- keeping products and materials in circulation at their maximum value
- supporting and restoring natural ecosystems (ADVANCE Circular, 2025).

Interest in the circular economy is largely due to attempts to translate the concept of “sustainable development” into theory, the implementation of which has proven difficult over time due to the generality of the topic, “more of a theoretical dream than an implementable reality” (Engelman, 2013). The circular economy is seen as a bridge, a way to put sustainable development into practice (Kirchherr, Reike and Hekkert, 2017). Table 1 presents the conceptual approaches to the circular economy.

Tabel 1 - The concept of "circular economy"

Authors	Conceptualizing the Circular Economy
Kirchherr, Reike and Hekkert, 2017	- economic system - the materials used in the production process can be used sparingly, reused, repurposed, and reintroduced into the economic cycle
Prieto-Sandoval, Jaca and Ormazabal, 2018	- economic system - a major conceptual shift in how humanity relates to nature and prioritizes goals related to resource conservation, closing material and energy loops, and supporting sustainable economic and social development.

Authors	Conceptualizing the Circular Economy
Suárez-Eiroa et al., 2019	- regenerative production-consumption system - aims to keep resource extraction levels, as well as waste and emissions generation, within sustainable limits by integrating a closed-loop system, minimizing its scale, and maximizing the duration of resource value retention within the system.

Source: Adapted from Suárez-Eiroa et al., (2019); Prieto-Sandoval et al. (2018).

An analysis of Table 1 leads to the conclusion that the circular economy is an economic or production-consumption system that broadly aims at sustainable development.

The development of the circular economy depends largely on how the life cycle of products is viewed. Stahel and Reday-Mulvey argue that

products currently in use can become future resources, whose value is influenced by the preceding economic context (Stahel and Reday-Mulvey, 1977). Thus, the circular economy is based on three main principles: reduction, reuse, and recycling. These principles are illustrated in Figure 1.

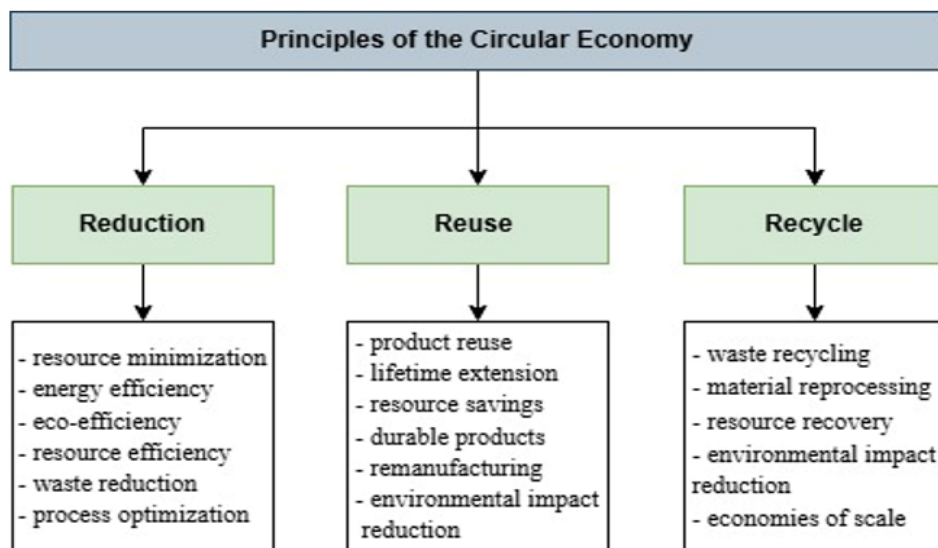


Figure 1 – The 3Rs

(Source: Adapted from Ghisellini et al. 2016)

The Principle of Reuse is based on the idea that a product or subassembly can be used multiple times without changing the purpose for which it was originally manufactured. The economic advantage lies in the minimal use of resources (human, financial, material) and reduced environmental impact (less energy consumption, reduced harmful emissions). Companies face new requirements: on the one hand, at the design stage, to enable the development of products with multiple-use cycles, and on the other hand, to develop strategies that

allow for the collection and remanufacturing of products after they have already reached the market (Ghisellini et al., 2016).

The principle of recycling aims to transform waste into new products, materials, or substances, either for their original use or for other purposes. The main advantage lies in minimizing environmental impact (eliminating the need to treat or dispose of certain wastes) and promoting the efficient use of resources that still retain their utility. The principle of recycling is constrained by factors

such as the irreversible degradation of materials (entropy), their complex structure, and high levels of use. The recycling process has a global dimension and follows the principles of industrial production, characterized by economies of scale, specialization, and labor cost optimization (Ghisellini et al., 2016).

The principle of reduction aims to limit resource use and waste generation by optimizing the efficiency of production and consumption processes, including the adoption of high-performance technologies, the design of lighter and more compact products, the simplification of packaging, and the promotion of sustainable consumption patterns. The eco-efficiency of production processes is determined by organizations' ability to improve the value performance of products, while simultaneously implementing plans to limit environmental impacts (by using fewer resources per product or replacing harmful materials with environmentally friendly alternatives) (Ghisellini et al., 2016).

The Role of Higher Education in Supporting Green Business Models

Studies show that continuing education plays a crucial role in the circular economy. Continuing education is supported by systemic changes, that is, by a fundamental shift in perspective. Universities or pre-university educational institutions can effectively support and implement lifelong learning if they succeed in identifying the right methods and practices in society, recognizing their impact, and if they have access to technology and infrastructure and establish open communication with key institutions in the community where they operate. Success lies in understanding the connection between these factors. (Moloney et al., 2010)

The circular economy entails a profound transformation of an organization's systems and is based on the connection between the environment, society, and the economy, with the success of its implementation being determined by internal systems. The circular economy must be viewed as an integrative discipline, with teaching and learning processes resulting from the combination of multiple perspectives. An education that supports

the circular economy creates a bridge between industry and academia. (Renfors, 2024)

Education for the circular economy can be conceptualized based on three dimensions: micro (through curriculum development), meso (through innovative teaching methodologies), and macro (through aligning policies with the interests of relevant stakeholders). At the micro level, the role of educational organizations is to support the formation and development of competencies that enable students to develop innovative strategies addressing sustainability and environmental challenges. At the meso level, universities must strive to promote learning through real-world experiences and interdisciplinary learning, engage in projects, and establish partnerships with key industry stakeholders. At the macro level, higher education institutions integrate the circular economy through policy development, considering the balance between the academic sector, the industrial sector, society, and government authorities, based on their institutional resources. (Kruja et al., 2025)

Methodological approach

This paper aims to examine the relationship between Green Business Models, circular economy principles, and higher education in order to identify the competencies required for preparing future professionals to support the green transition. More specifically, the study seeks:

- to clarify the conceptual relationship between Green Business Models and the circular economy;
- examine the European policy framework relevant to sustainability and higher education;
- to identify the competencies required for the implementation of Green Business Models in organizational practice.

This paper was developed through a qualitative review and synthesis of the relevant literature and official policy documents issued by the European Commission. The literature was selected to examine the relationship between Green Business Models, circular economy principles, higher education, and competency development. Both conceptual and empirical studies were analyzed in order to identify the competencies required for supporting the

implementation of Green Business Models in organizational practice.

In addition, European strategic and legislative documents related to sustainability, lifelong learning, and the green transition were reviewed to identify the competencies promoted at the policy level. The literature search was conducted using academic databases including Web of Science, ScienceDirect, Emerald, ResearchGate, and EUR-Lex, employing keywords such as Green Business Models, circular economy, higher education, sustainability competences, and green skills.

Results and Discussion

In 2018, the Council of the European Commission issued a document setting out recommendations on lifelong learning competencies. These recommendations can serve as starting points for the organizational development of educational institutions (The Council of the European Union, 2018). Table 2 presents some of the general competencies defined by the Council, which can support curriculum development.

Table 2 - General competences

Category	Competence
Mathematical competence and competence in science, technology and engineering	• technology and technological products and processes • understanding of the impact of science, technology, engineering and human activity in general • the ability to use logical and rational thought • support for both safety and environmental sustainability
Digital competence	• creativity and innovation • use of different devices, software, and networks • problem solving and critical thinking
Citizenship competence	• awareness of sustainable systems • responsibility for the environment • engage with others in common or public interest
Entrepreneurship competence	• critical and constructive reflection within evolving creative processes and innovation • understand approaches to planning and management of projects • mobilize resources

Source: The Council of the European Union, 2018

The European Commission supports general competencies, which can be considered starting points for the development of educational plans.

In the literature, researchers have defined the specific competencies required for the implementation of circular economy studies. Sanna-Mari Renfors conducted a bibliometric study to identify the necessary competencies that circular economy courses should address. She started from the premise that the circular economy is the result

of the interaction of multiple systems, which is why systems thinking should play a crucial role. Kruja et al. and Trevisan et al. developed a holistic framework of competencies necessary for the circular economy. (Kruja et al., 2025; Trevisan et al., 2025) Based on the main categories of competencies defined by the European Council, Table 3 lists the specific competencies highlighted by the studies.

Table 3 - Specific competencies

Category	Competence
Mathematical competence and competence in science, technology and engineering	• resource management • systems thinking • circular design • eco-design • life cycle assessment (LCA) • energy management skills • analytical skills • problem-solving
Digital competence	• data management skills • programming skills • design digital services and PSS • master 3D printing • VAM realities • Robotics skills • automation skills
Citizenship competence	• circular collaboration • value-based thinking • reflective competence teamwork • communication
Entrepreneurship competence	• development of circular business models • decision-making • leadership • networking • solving entrepreneurial problems

Source: Kruja et al., 2025; Trevisan et al., 2025; Renfors, 2024

Systems thinking is an essential skill in the circular economy, involving the ability to analyze the connections between environments, evaluate decisions, and manage crises through the synergy and commitment of all stakeholders. Circular design refers to the ability to develop products and/or processes in accordance with eco-design requirements, and to modifications made to the product life cycle so that it supports recycling, reuse, or resource reduction (Renfors, 2024).

Competencies related to circular business models prepare students to identify agents of change in the environment, as well as the opportunities and limitations that may influence the organization, fostering an understanding of reality and openness to the laws governing the circular economy (Renfors, 2024).

Circular collaboration as a competency refers to developing the ability to see the connections between companies and how they can manage their resources through mutual support in order to reduce their environmental impact. Value-based thinking refers to upholding the principles of the circular economy and analyzing the fundamental values associated with the issues at hand. Collaboration, leadership, and critical thinking become necessary skills in an organization that must manage and address uncertain situations related to sustainability (Renfors, 2024).

Digital competencies support the evaluation of circular system performance, the monitoring of resource flows, the identification of solutions in circular processes, the development of new circular

business models, the optimization of product design, and the automation of production flows (Trevisan et. al., 2025).

Conclusions

The transition towards a sustainable economy requires organizations to adopt business models capable of integrating environmental, economic, and social objectives into their core activities. In this context, Green Business Models represent an important strategic approach for creating long-term value while responding to increasingly complex sustainability challenges. Among the different approaches discussed in the literature, the circular economy stands out as one of the most practical frameworks for translating sustainability principles into organizational practice through resource efficiency, product life-cycle extension, and value retention.

The findings of this study underline the strategic contribution of higher education institutions to the green transition. Universities are

not only providers of knowledge but also key actors in preparing graduates capable of designing, implementing, and managing Green Business Models. Achieving this objective requires curricula that combine technical expertise with entrepreneurial thinking, digital capabilities, sustainability awareness, and transversal competences that enable graduates to respond to complex and rapidly changing business environments.

The findings of this study indicate that the implementation of Green Business Models requires a multidisciplinary combination of competencies rather than isolated technical knowledge. Technical, sustainability-related, entrepreneurial, digital, and transversal competencies complement one another in preparing graduates to address complex sustainability challenges and support organizational innovation. Therefore, higher education curricula should adopt an integrated approach that fosters these competencies and reflects the interconnected nature of sustainability, circular economy principles, and business transformation.

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Sustainable Mobility Preferences in two Romanian Cities

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Abstract

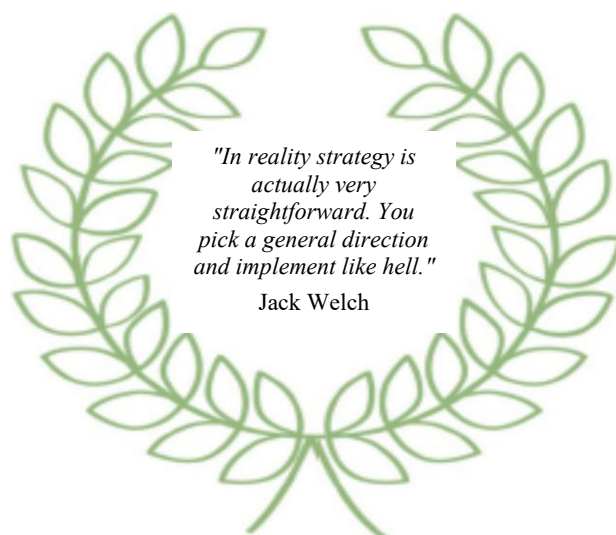
This paper examines sustainable urban mobility preferences in two Romanian cities, Bacău and Cluj-Napoca, using open survey data from a wider European study. The analysis is based on a Romanian subsample of 1,000 respondents, with 500 observations from each city. The selected variables cover earlier use of public transport and private cars, comfort with transport modes, access to public transport services and conditions that may support future intermodal planning. The results show a stronger public transport profile in Cluj-Napoca and a more car-oriented profile in Bacău. The model reached a Nagelkerke R^2 of 0.241 and an overall classification accuracy of 71.6%. The findings suggest that access to public transport is important, but it should be considered together with local travel habits, comfort and the quality of connections between transport modes.

Keywords: sustainable urban mobility, public transport, user perceptions

Introduction

Urban mobility has an important role in the daily life of a city. People need simple and reliable ways to reach work, education, public services, shopping areas and leisure activities. When daily travel depends mainly on private cars, cities face more congestion, higher energy use and greater pressure on public space. For this reason, sustainable urban mobility is increasingly linked to the use of public transport, walking, cycling and combinations between these travel options. Recent research on future urban mobility shows that cities are moving towards transport systems in which public services, shared options and active travel must work together in a more coordinated way (Miskolczi et al., 2021).

Public transport has a central place in this process. It can serve large numbers of people and can support access to urban opportunities without requiring each traveler to use a private car. However, the existence of a bus, tram or metro



service does not automatically mean that citizens will use it often. People also consider how easy the service is to reach, whether it connects them to their usual destinations, how often it operates and how comfortable they feel when using it. Studies on

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public transport service quality show that users' perceptions are closely related to satisfaction and to their intention to continue using collective transport (Ismael and Duleba, 2021; de Oña, 2022).

This user perspective is important for urban management. Transport plans are often built around infrastructure, lines, vehicles and operating costs. These elements are necessary, but they do not describe the full travel experience. A service may be technically available while still being seen as inconvenient by the people who should use it. For example, a station may be too far from home, a connection may require difficult transfers, or the available lines may not provide direct access to important destinations. Research on public transport management has shown that decisions on sustainability and innovation need to consider how citizens understand and value the service offered to them (Gómez-Ortega et al., 2024).

Travel choices also depend on personal and household conditions. Age, education, employment, income, access to a private car and the purpose of a journey can shape the choice between public transport and individual travel. A study on sustainable modal choices in the Porto metropolitan area found that personal characteristics and vehicle ownership were associated with differences in travel preferences (Rocha, 2023). These factors are relevant for Romanian cities as well. Two people living in the same urban area may respond differently to the same transport offer because their work arrangements, family duties or access to alternative means of transport are different.

The way in which people connect to public transport is also important. Sustainable mobility is not limited to the use of a single means of transport. In practice, a journey may include walking to a station, using a bus or metro line, changing between services, or combining public transport with cycling or park-and-ride facilities. Mobility hubs and connected services are intended to make such combinations easier and more attractive. Recent work on mobility hub planning describes these places as points where public transport, pedestrian access, cycling and shared mobility can meet in a single travel system (Pimenta and Kamruzzaman, 2024). This idea is relevant for a wider research

direction on intermodal transport. Still, before studying physical transport connections in detail, it is useful to understand whether citizens have access to public transport and how they perceive the available travel options.

The period following the COVID-19 outbreak offers a useful setting for studying these questions. Restrictions, health concerns and changes in work habits affected daily travel in many cities. Public transport use declined for some groups, while walking, cycling, private car use and work from home became more important in different contexts. A systematic review of mobility behavior during the pandemic showed that travel habits changed across several transport modes and that these changes raised new questions for sustainable urban planning (Benita, 2021). Another study found that the greater use of telework and online services was related to changes in mobility needs and everyday travel behavior (Mouratidis and Papagiannakis, 2021). Although the present paper is not focused only on the pandemic, the available survey data offers a useful picture of how people assessed transport choices during a period of visible change.

This topic is also important because the use or non-use of public transport cannot be explained only by environmental arguments. People may support sustainable mobility in general, while still choosing a private car when public transport does not meet their practical needs. A survey-based study of local public transport use found that the quality of the travel experience and the reasons for not using the service are useful for understanding travel choices (Bina and Biassoni, 2023). Therefore, a study of mobility preferences should examine both sustainable options and the everyday conditions that make these options acceptable to users.

Romanian cities need evidence of this kind. Urban mobility policies are expected to support cleaner and more connected travel, but local decisions should be informed by the way people actually use and evaluate transport services. In the case of a future research program focused on intermodal transport integration in Bucharest, an initial behavioral analysis can provide a useful basis. It can show how Romanian urban residents relate to public transport, private car use, walking

and cycling. It can also indicate whether access to a stop, the availability of different public transport lines and the connection to main destinations are associated with more favorable mobility patterns.

This paper uses open survey data from the study “Survey on urban transport in the aftermath of the COVID-19 outbreak: Data from 20 cities across Europe”. The original dataset contains 10,000 respondents from European urban areas and includes two Romanian cities: Bacău and Cluj-Napoca (Navajas-Cawood et al., 2023). The questionnaire covers socio-demographic characteristics, transport use, changes in mobility habits, comfort with different modes, access to public transport and the availability of nearby transport connections. In particular, it includes questions about walking access to stations, available bus and rail or metro lines, connections to main destinations and park-and-ride options. These variables describe access conditions that may favor connected travel, although the dataset does not record complete intermodal journeys made by respondents.

Digital tools also make it easier to work with open datasets in a clear and repeatable way. Python has become a practical choice for applied studies because it can support data preparation, software functions, visual outputs and decision-oriented analyses in different fields. Recent studies have used Python-based solutions for personalized support, urban transport accessibility, robotic path planning, open-data mobility analysis and data-based classification tasks (Dragoi et al., 2025; Nieland et al., 2025; Cristoiu et al., 2026; Fink et al., 2024; Dragoi et al., 2026a; Tenkanen, Chau and Dey, 2024). This wide use supports its role in the present study, where Python is not used to create a complex prediction system, but to prepare the open survey file, select the Romanian cases, retain the relevant variables and produce a clean dataset for analysis. After this preparation stage, JASP provides a suitable environment for examining survey responses through descriptive statistics, group comparisons and regression models. Recent survey-based studies have applied this type of statistical workflow in both educational decision-support and transport behavior research (Buzducea

et al., 2026; Schasché, Wankmüller and Hampl, 2023; Dragoi et al., 2026b; Basalim, 2024). Thus, the combined use of Python and JASP offers a simple and reproducible path from open raw data to results that can support urban mobility planning.

Accordingly, the aim of this paper is to examine sustainable mobility preferences and public transport perceptions in two Romanian cities using open survey data. The analysis focuses on three questions: first, how respondents used public transport, private cars, walking and bicycles; second, how respondents assessed access to and comfort with public transport; and third, whether selected personal and accessibility factors are related to frequent public transport use. The study is based on a Romanian subsample of 1,000 respondents, equally divided between Bacău and Cluj-Napoca. The results are intended to support an early behavioral understanding of sustainable urban mobility in Romania and to provide a basis for later research on intermodal transport integration in Bucharest.

Methodology of research

This study uses open survey data published in 2023 as part of a European study on urban transport behavior (Navajas-Cawood et al., 2023). The original dataset contains 10,000 respondents from 20 urban areas. The present paper focuses on the Romanian subsample, which includes 500 respondents from Bacău and 500 respondents from Cluj-Napoca. The sample analyzed therefore contains 1,000 observations.

The questionnaire includes information on personal characteristics, earlier transport use, reported changes in mobility behavior, comfort with different travel modes and access to public transport. For this paper, the main variables refer to walking, bicycle use, private car use, urban public transport use, comfort with public transport, walking access to a stop or station, nearby public transport line types and connection to main destinations. The availability of bus and train or metro services near the home is used as an indicator of conditions that may support connected travel. It

does not show that respondents completed intermodal journeys.

The original raw_data.tab file was prepared through a short Python procedure. First, the procedure selected only respondents identified with the country code RO. Second, it retained the variables related to the purpose of the paper and removed unused questionnaire branches and postal-code information. Third, answers such as “do not know”, “not applicable” and “never used this mode” were treated as missing values only when they did not provide usable information for the analyzed variable. No Romanian respondent was deleted. The final CSV file imported into JASP contains 1,000 respondents and 50 variables.

The analysis uses four derived indicators: *frequent_pt_user_before* identifies respondents who used urban public transport at least two or three days per week before the outbreak, *frequent_car_driver_before* identifies frequent private car users, *pt_access_within_walking_distance* identifies respondents who reported that public transport was within walking distance from home, *pt_bus_rail_combination_near_home* identifies respondents who reported access to both bus and train or metro services near home. A fifth indicator, *good_pt_connection_binary*, records whether nearby public transport provided a good connection to the respondent’s main destinations.

The statistical analysis is conducted in JASP. First, frequency tables are used to describe the sample, earlier travel behavior, public transport

comfort and access conditions. Second, chi-square tests are used to compare Bacău and Cluj-Napoca for binary mobility and accessibility indicators. Third, the Mann-Whitney U test is used to compare the two cities in relation to ordinal measures, especially comfort with public transport. Finally, binary logistic regression is used to examine factors associated with frequent public transport use. The analysis reports odds ratios, significance values and classification accuracy, and the results are interpreted as statistical associations rather than causal effects.

A binary logistic regression model is also considered. The model examines frequent public transport use in relation to city, frequent private car use, walking-distance access to public transport, availability of combined bus and train or metro services, and perceived connection to main destinations. The model is used to complement the descriptive, chi-square and Mann-Whitney results, while remaining within the limits of the available survey data.

Results and discussion

The descriptive analysis was first used to obtain a general view of mobility behavior and public transport access in the Romanian sample. The analyzed dataset contains 1,000 respondents, equally distributed between Bacău and Cluj-Napoca. Table 1 presents the main results based on the valid answers available for each indicator.

Table 1 – Main mobility and public transport indicators

Indicator	Valid responses	Positive responses	Valid percentage
Frequent public transport use before the outbreak	1000	333	33.3%
Frequent private car use as driver before the outbreak	1000	554	55.4%
Public transport within walking distance from home	945	781	82.6%
Bus and rail/metro combination available near home	851	170	20.0%
Good public transport connection to main destinations	841	770	91.6%
Reduced public transport use during restrictions	804	489	60.8%

(Source: calculations based on Navajas-Cawood et al. 2023).

The same descriptive indicators are presented visually in Figure 1, in order to make the main

differences between mobility behaviors and access conditions easier to observe.

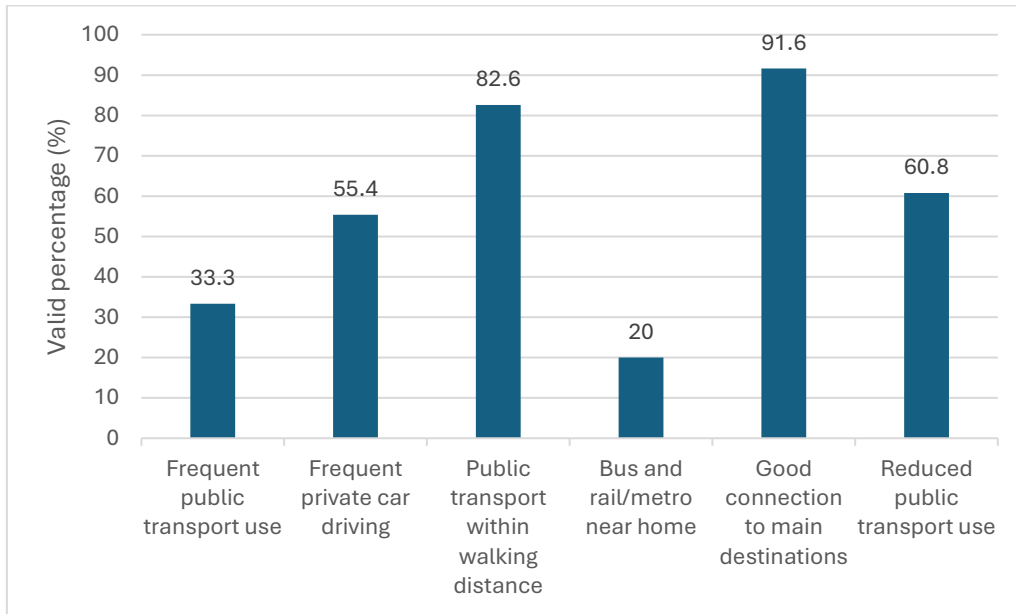


Figure 1 – Visual overview of mobility and public transport indicators

The results show that frequent car use was more common than frequent public transport use before the outbreak. While 55.4% of respondents reported frequent use of a private car as driver, only 33.3% reported frequent use of urban public transport. At the same time, access to public transport was rated positively. Among respondents with valid answers, 82.6% reported that a stop or station was within walking distance from their home, and 91.6% stated that the available lines provided a good connection to their main destinations.

A different result appears for the availability of connected transport options. Only 20.0% of valid respondents reported access to both bus and rail or metro services near their home. This suggests that basic public transport access is much more common than access conditions that may support transfers between different public transport modes. The result

is useful for future intermodal planning, although it does not show whether respondents used more than one mode during the same journey.

Changes in public transport use were also visible in the survey data. Among respondents who provided a valid answer, 60.8% reported using public transport less often during the restriction period. This finding must be read in relation to the survey context, when daily travel was influenced by health concerns and changing work or activity patterns. Still, it indicates that access to a service does not alone ensure continued use when travel conditions change.

Public transport comfort was examined separately because it reflects how respondents evaluated the travel experience. The valid answers are presented in Table 2.

Table 2 – Expected comfort with urban public transport

Response category	Frequency	Valid percentage
Not at all comfortable	160	19.2%
Not very comfortable	268	32.1%
Fairly comfortable	334	40.0%
Very comfortable	73	8.7%
Total valid responses	835	100.0%

(Source: calculations based on dataset published by Navajas-Cawood et al. 2023).

The distribution of comfort answers is presented visually in Figure 2.

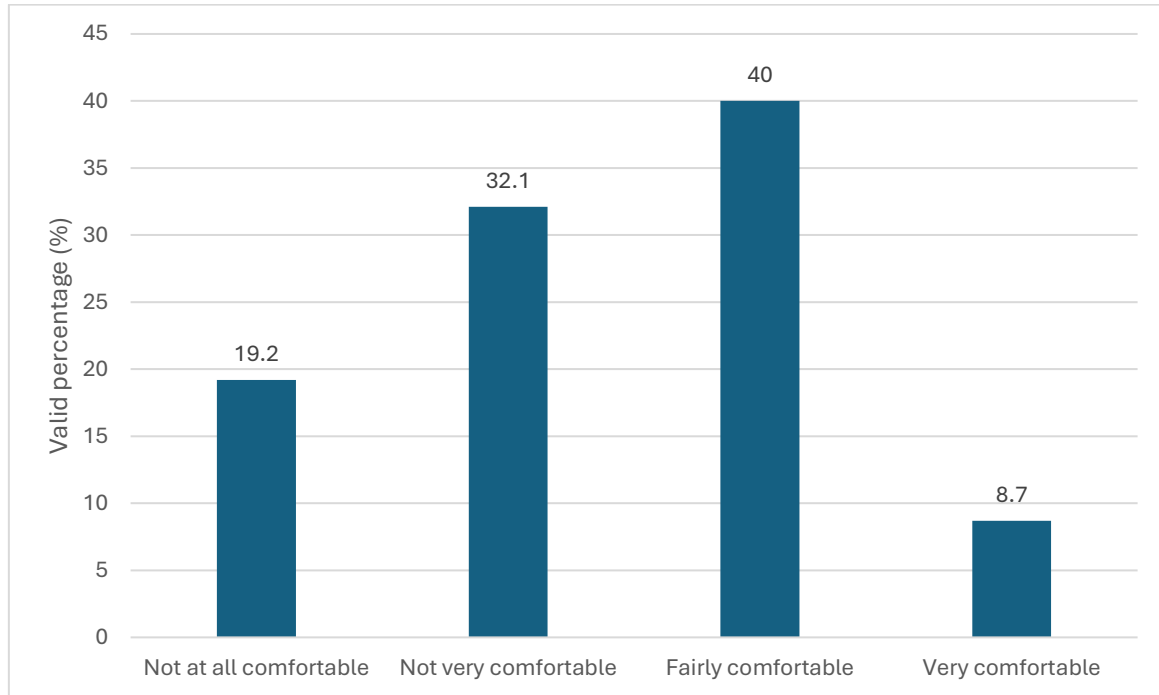


Figure 2 – *Distribution of expected comfort with urban public transport*

The comfort responses are divided almost equally between the two directions. Low comfort was reported by 51.3% of respondents with valid answers, while 48.7% reported high or very high comfort. Thus, the data does not show a clear general perception of public transport as either comfortable or uncomfortable. The original questionnaire also included the intermediate answer

As comfortable as before, but this category was not present in the Romanian subsample. For this reason, the comfort results are interpreted cautiously and will be supported by the subsequent comparison between the two cities.

To compare the two cities, chi-square tests were applied to the main binary indicators. The results are presented in Table 3.

Table 3 – *Differences between Bacău and Cluj-Napoca*

Indicator	Bacău	Cluj-Napoca	χ^2	p	Cramer's V
Frequent public transport users	22.2%	44.4%	55.472	< .001	0.236
Frequent private car drivers	61.8%	49.0%	16.577	< .001	0.129
Public transport within walking distance	79.7%	85.6%	5.748	.017	0.078
Bus and rail/metro combination near home	19.0%	20.9%	0.495	.482	0.024
Good connection to main destinations	88.3%	94.7%	11.033	< .001	0.115
Reduced public transport use during restrictions	66.5%	56.1%	8.950	.003	0.106

(Source: calculations based on Navajas-Cawood et al. 2023).

The main differences between the two cities are also illustrated in Figure 3.

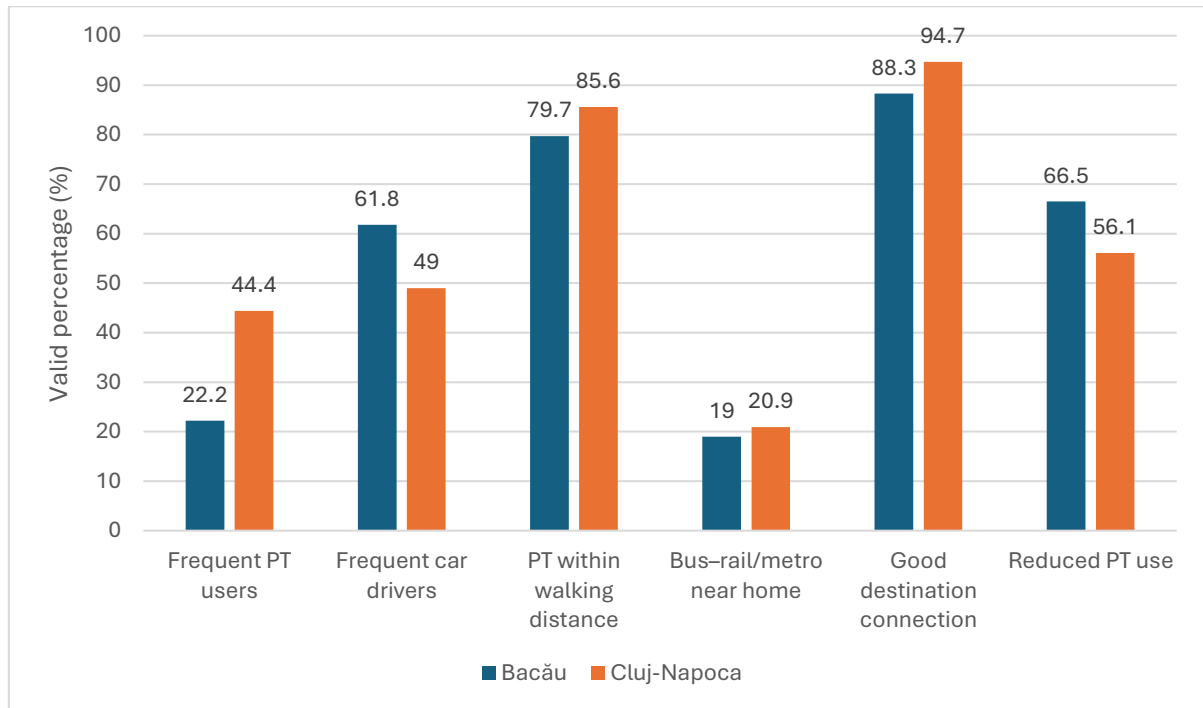


Figure 3 – Visual comparison of mobility indicators by city

The strongest difference between the two cities is related to public transport use. In Cluj-Napoca, 44.4% of respondents were frequent public transport users before the outbreak, compared with 22.2% in Bacău. The association was statistically significant, $\chi^2(1) = 55.472$, $p < .001$, with a small to moderate effect size. This result suggests that public transport had a stronger role in regular mobility behavior in Cluj-Napoca.

The opposite pattern appears for private car use. In Bacău, 61.8% of respondents were frequent private car drivers, compared with 49.0% in Cluj-Napoca. This difference was also statistically significant, $\chi^2(1) = 16.577$, $p < .001$, although the effect size was small. Together with the previous result, this shows a clearer car-oriented pattern in Bacău and a stronger public transport orientation in Cluj-Napoca.

Access conditions also differed between the two cities. Public transport within walking distance was reported by 85.6% of respondents in Cluj-Napoca and by 79.7% in Bacău, $\chi^2(1) = 5.748$, $p = .017$. A

good connection to main destinations was also more frequent in Cluj-Napoca, with 94.7% compared with 88.3% in Bacău, $\chi^2(1) = 11.033$, $p < .001$. These differences are statistically significant, but the effect sizes are small. Therefore, they should be interpreted as practical tendencies rather than large gaps between the cities.

The availability of both bus and rail or metro services near the home did not differ significantly between the two cities. The valid percentages were close: 19.0% in Bacău and 20.9% in Cluj-Napoca, $\chi^2(1) = 0.495$, $p = .482$. This result confirms that access to more than one public transport mode was limited in both cities. From an intermodal planning point of view, this is one of the most relevant findings, because it shows that basic access to public transport is more common than access to connected public transport options.

The reduction in public transport use during the restriction period was stronger in Bacău. Among valid responses, 66.5% of respondents in Bacău reported reduced public transport use, compared

with 56.1% in Cluj-Napoca. The difference was statistically significant, $\chi^2(1) = 8.950$, $p = .003$, with a small effect size. This suggests that public transport use was more affected in Bacău during the analyzed period.

Overall, the comparison shows two different profiles. Cluj-Napoca has higher frequent public transport use, better walking access and stronger perceived connections to main destinations. Bacău has higher frequent car use and a stronger reported reduction in public transport use. However, both cities show a low level of nearby bus and rail or

metro combination. This means that future mobility policies should not focus only on access to a stop or station, but also on the quality of connections between modes of transport.

The comparison of public transport comfort was made with the Mann–Whitney U test, because the variable is ordinal. The result showed a statistically significant difference between the two cities, $U = 64273.500$, $p < .001$. The rank-biserial correlation was -0.258 , indicating a small to moderate difference. The descriptive values for each city are presented in Table 4.

Table 4 – Public transport comfort by city

City	Valid responses	Mean	SD	Mean rank
Bacău	384	2.531	1.353	359.879
Cluj-Napoca	451	3.160	1.279	467.487

(Source: calculations based on Navajas-Cawood et al. 2023).

The difference in mean ranks is also shown in Figure 4.

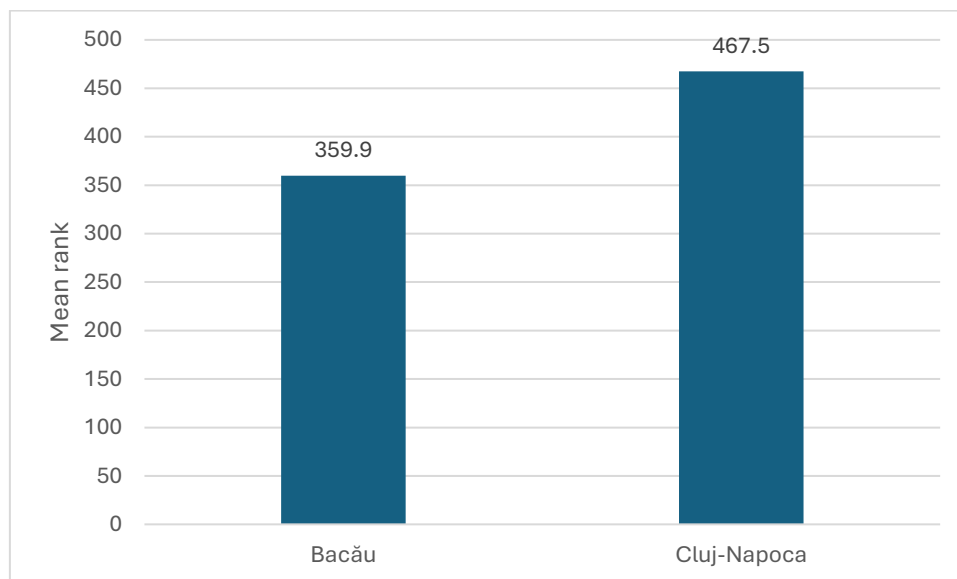


Figure 4 – Mean-rank comparison of public transport comfort by city

This result supports the previous findings. Cluj-Napoca had a higher share of frequent public transport users, better walking access and stronger perceived connections to main destinations. It also had a more favorable comfort evaluation. Bacău, on the other hand, showed higher frequent car use and a stronger reduction in public transport use during

the restriction period. Taken together, the findings suggest that public transport in Cluj-Napoca had a stronger user position in the analyzed sample, while Bacău showed a more car-oriented and more fragile public transport profile.

From a management point of view, the results show that sustainable mobility planning should not

focus only on the presence of public transport. Access, perceived connection to destinations and comfort also matter. The low share of respondents with access to both bus and rail or metro services near home is also important. It suggests that future intermodal planning should give more attention to the quality of connections between modes of transport, not only to the existence of individual services.

To further examine frequent public transport use, a binary logistic regression model was estimated. The dependent variable was frequent public

transport use before the outbreak. The predictors were city, frequent private car use, walking-distance access to public transport, availability of bus and rail or metro services near home, and good connections to main destinations. The model was statistically significant compared with the null model, $\Delta\chi^2 = 161.842$, $p < .001$. The Nagelkerke R^2 value was 0.241, and the overall classification accuracy was 71.6%.

The main regression results are presented in Table 5.

Table 5 – Logistic regression model for frequent public transport use

Predictor	Estimate	Odds ratio	p
City: Cluj-Napoca	0.980	2.665	< .001
Frequent private car driver	-1.544	0.214	< .001
Public transport within walking distance	0.409	1.506	0.148
Bus and rail/metro combination near home	0.332	1.394	0.091
Good connection to main destinations	0.266	1.305	0.395

(Source: calculations based on Navajas-Cawood et al. 2023).

The odds ratios from the regression model are also illustrated in Figure 5.

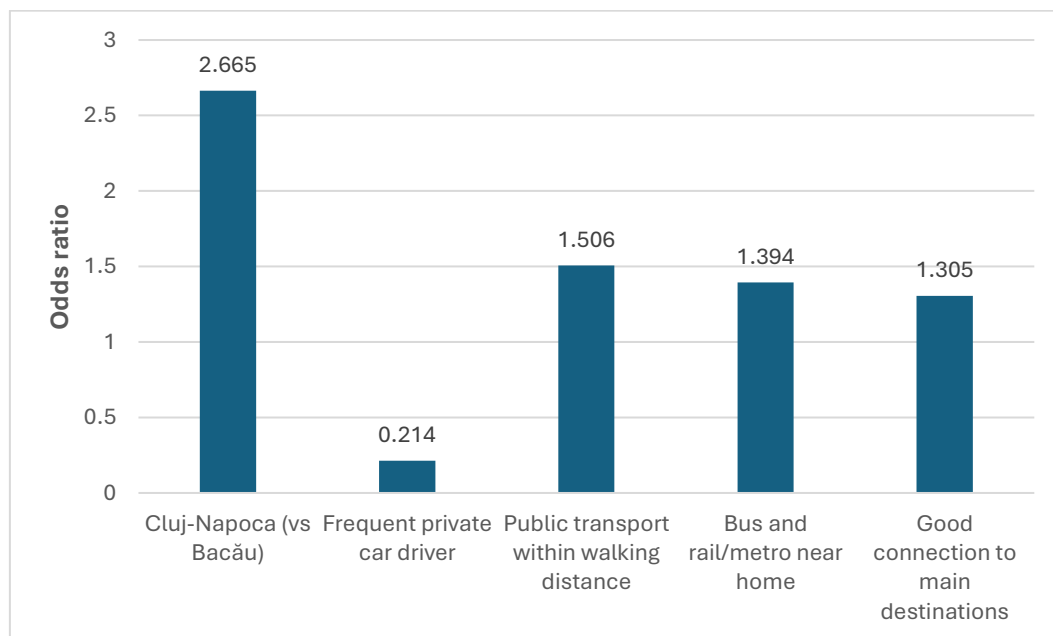


Figure 5 – Odds-ratio profile for frequent public transport use

The regression confirms the main descriptive pattern. Respondents from Cluj-Napoca had higher odds of being frequent public transport users than

respondents from Bacău. The odds ratio was 2.665, meaning that the odds were more than twice as high for Cluj-Napoca, after the other variables in the

model were included. Frequent private car use had the opposite effect. Frequent car drivers had much lower odds of being frequent public transport users, with an odds ratio of 0.214.

The access variables had positive odds ratios, but they were not statistically significant in this model. This means that walking-distance access, the presence of both bus and rail or metro services near home, and good connections to main destinations were not enough to explain frequent public transport use after city and frequent car driving were included. This result suggests that public transport behavior depends not only on the existence of access conditions, but also on broader local mobility habits and car dependence.

Conclusions

This paper examined sustainable mobility preferences and public transport perceptions in two Romanian cities, Bacău and Cluj-Napoca, using open survey data from a wider European urban transport study. The analysis used a Romanian subsample of 1,000 respondents and focused on public transport use, private car use, access conditions, comfort and reported changes in mobility behavior.

The results show that private car use had a stronger position than public transport in the general Romanian sample. Frequent private car driving was reported by 55.4% of respondents, while frequent public transport use was reported by 33.3%. At the same time, most respondents with valid answers reported that public transport was within walking distance from home and that available lines provided a good connection to their main destinations. This shows that access to public transport existed for many respondents, but this access did not automatically lead to frequent use.

The comparison between the two cities showed different mobility profiles. Cluj-Napoca had a higher share of frequent public transport users, better walking access, stronger perceived connections to main destinations and higher

comfort levels. Bacău had a higher share of frequent private car drivers and a stronger reduction in public transport use during the restriction period. These findings suggest that public transport had a stronger user position in Cluj-Napoca, while Bacău showed a more car-oriented mobility profile.

The logistic regression model confirmed this pattern. Respondents from Cluj-Napoca had higher odds of being frequent public transport users than respondents from Bacău. Frequent private car driving had the opposite association and strongly reduced the odds of frequent public transport use. The access variables had positive odds ratios, but they were not statistically significant in the model. This suggests that public transport behavior is linked not only to the presence of services, but also to local travel habits and car dependence.

A relevant finding for future intermodal planning is the low share of respondents who reported both bus and rail or metro services near home. This result was similar in the two cities and remained around one fifth of valid responses. Therefore, future sustainable mobility policies should not focus only on access to a stop or station. They should also consider how different transport modes are connected and how easy it is for users to move between them.

The study has several limits. The data refer only to Bacău and Cluj-Napoca, not to Bucharest. The survey was collected in the context of the COVID-19 period, so the results should not be treated as a direct description of current travel behavior. Also, the dataset does not record complete intermodal journeys. It only describes access conditions, reported behavior and user perceptions.

Even with these limits, the paper provides a useful starting point for understanding sustainable mobility behavior in Romanian cities. The use of Python for data preparation and JASP for statistical analysis offered a simple and reproducible workflow. Future research can extend this work by using direct data from Bucharest, spatial transport data, GTFS files and dedicated surveys on intermodal trips, transfers and user experience.

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Design a Green Supply Chain Management using Machine Learning

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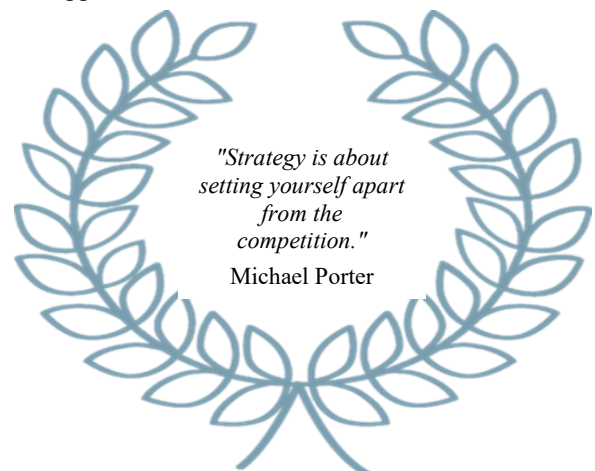
Abstract

This article introduces Green Supply Chain Mapper, an app for assessing green supply chain scenarios built using PySimpleGUI and based on Python. Sustainability, renewable energy, emissions, resource utilization, waste, energy consumption, and cost are some of the topics covered by the public dataset that the framework draws from, which has one thousand records and variables. The program evaluates five machine learning classifiers, computes a green performance score, and allocates situations to low, medium, and high-performance classes. File selection, analysis configuration, visual result generation, and structured output export are all made possible via the graphical user interface. Through transparent ranking, class labeling, and classifier comparisons, the findings demonstrate that the suggested solution may bolster green supply chain management.

Keywords: decision support, supply chain, machine learning, Python application

Introduction

Increasingly, businesses are looking to green supply chain management as a way to boost profits while cutting down on waste. Cost, time, and delivery indicators are no longer the only metrics used to examine supply chains in this environment. Energy usage, resource consumption, emissions from transportation, trash reduction, and sustainable business decisions are all interconnected. Green supply chain management is a relatively new concept that, according to studies, connects operational choices with environmental cooperation, innovative capability, and



organizational success (Jo and Kwon, 2021; Hariyani et al., 2024; Makhdoom et al., 2025).

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Simultaneously, businesses want user-friendly digital resources that can convert massive operational numbers into actionable management data. It may be challenging for many businesses to make daily choices based on the data they acquire about suppliers, transportation, energy, expenses, and emissions. When complicated data is transformed into understandable outputs, reports, and visual indications, practical applications may assist users, according to prior software-oriented research (Sarkar, 2021; Dragoi et al., 2025c). Recent studies on environmentally responsible distribution and sourcing have followed similar trends, seeing green supply chain management as a real-world discipline that requires strategic and data-based backing (Nozari, 2024; Barman, 2025).

Machine learning (ML) and digital analytics are finding more and more applications in supply chain management as a result of their ability to detect trends that would be difficult to detect manually. These techniques may lend a hand with sustainable supply chain decision-making, performance grouping, ranking, and categorization. Procurement, production planning, inventories, logistics, and sustainable operations are some of the areas where machine learning has recently been the subject of research (Vishwakarma et al., 2025; Drouzi and Rajaa, 2026). The use of predictive models to bolster managerial choices based on structured data is an older area of machine learning research that is compatible with this trend (Teixeira et al., 2025; Buzducea et al., 2026).

Sustainability and data-driven management go hand in hand, which is particularly helpful for environmentally friendly company models. Measurable indicators should be used in conjunction with a green business model's stated environmental aim when evaluating it. Some examples of these metrics include operating cost, supplier behavior, delivery performance, energy usage, emissions, waste, and resource utilization. Companies may benefit from data-based models in their pursuit of knowledge about the interplay of technology, sustainability, and financial success, according to studies on green supply chains and digital transformation (Kumar et al., 2022; Liao et al., 2024). Here, ML may serve as a useful intermediary between unprocessed data and the interpretations made by management.

The present article follows an applied software-based approach. This approach has already been used in recent research where Python applications were designed to support analysis, prediction, visualization, or interaction with real data. Examples include software applications for personalized learning, offline intelligent platforms, and comparative data-processing frameworks (Romero and Ventura, 2020; Masiello et al., 2024; Dragoi et al., 2025b; Cukurova, 2025; Dragoi et al., 2026a). These contributions show that a clear software workflow can make data analysis more accessible for non-specialist users, especially when the application includes a graphical interface and structured outputs.

The proposed work also follows the logic of management-oriented analytics. Instead of developing only a theoretical model, it presents a working application that loads a public dataset, processes selected variables, computes indicators, applies machine learning classifiers, and exports results for interpretation. This type of applied workflow has also been used in previous FAIMA-oriented work, where raw educational platform data were converted into visual indicators for academic management (Dragoi et al., 2026b). In a similar way, green supply chain data can be converted into managerial indicators for comparing business scenarios.

Green supply chain management is also linked with broader sustainability and circular economy discussions. Companies are expected to reduce environmental impact across the whole chain, from sourcing and production to logistics, distribution, and waste handling. Previous research on photovoltaic waste recovery shows that sustainability decisions often require ranking alternatives and comparing several criteria at the same time (Wu and Zuo, 2023; Nechita et al., 2026). Other studies on sustainable supply chains also point to the need for digital decision-support systems able to combine environmental and business indicators (Hasan, Khan and Wuest, 2024; Sharma, 2026).

From a methodological point of view, machine learning classifiers are appropriate for this type of application because they can group supply chain scenarios into performance categories. Classifiers may sort input variables into categories such as

low, medium, and high green performance, for instance. The findings of lightweight classifiers, such as tree-based approaches, are simpler to explain in managerial situations, making them helpful. There is prior experience with classifier-based reasoning in applied Python research, where a replicable framework was utilized to evaluate many lightweight models (Heydarbakian and Spehri, 2022; Dragoi et al., 2026c). Planning, risk analysis, and sustainability-oriented categorization are some of the other uses of machine learning in supply chain research (Wasi, Islam and Akib, 2024; Khaleghi et al., 2025).

The suggested framework relies significantly on the graphical interface. The user may pick the input file, analyze it according to their preferences, run classifiers, and get results all without touching the code thanks to PySimpleGUI. Management users should find this useful since they often need a script in addition to an easily available decision-support tool. Combining algorithms with practical interfaces and operational outputs has been shown valuable in previous studies on interactive software, robot control, Python validation routines, and machine learning libraries (Montiel et al., 2021; Zhang et al., 2025; Dragoi et al., 2026d; Cristoiu et al., 2026a; PySimpleGUI, 2026; Cristoiu et al., 2026b).

This article makes use of a public dataset on green supply chains that can be found on Kaggle. It includes data from the supply chain that includes characteristics like energy use, transportation emissions, cost efficiency, and resource utilization (Ziya07, 2025). The suggested program may use these parameters to categorize supply chain situations and calculate an eco-performance score. By using a publicly available dataset, we can increase openness and make the experiment more reproducible. The article's goal is to provide a realistic framework that may be utilized or modified, not just one specific study, therefore this is vital (Dragoi et al., 2024).

Applied research that used data-driven algorithms, computer vision, multithreading, and predictive modeling to convert technical data into actionable choices or system actions (Ali et al., 2022; Galanti et al., 2023; Talingă et al., 2024; Scikit-learn Developers, 2025; Dragoi et al.,

2025a; Bojanowska and Kulisz, 2025) further supports the broader applicability of this software-oriented strategy. The practical principle that these studies support is that data-driven software may simplify the analysis, comparison, and management of complex processes, regardless of the domains in which they are used. The current scenario involves transferring this reasoning to green supply chain management, which involves processing sustainability data and business indicators simultaneously using a straightforward machine learning program built in Python (Dragoi et al., 2023).

This study primarily contributes a decision-support framework for environmentally conscious supply chain management. This system integrates open-source data with graphical user interfaces, sustainability-focused scoring, machine learning-based categorization, and exportable outcomes. Its purpose is not to supplant management discretion but to provide a more solid foundation upon which to compare supply chain scenarios from an economic and ecological vantage point.

Methodology of research

For the purpose of analyzing green supply chain situations, the suggested technique was developed as a standalone Python program. A CSV dataset is loaded, a green performance score is computed, each scenario is assigned a performance class, and several machine learning classifiers are compared by the program. The goal is to provide management with findings that may be utilized to analyze supply chain indicators.

Obtaining the green supply chain dataset 1000.csv file from the Green Supply Chain Dataset hosted on Kaggle was the first step in doing this investigation (Ziya07, 2025). Twelve columns and one thousand records make up the dataset. Several components of supply chain performance are described by the variables. These include renewable energy, CO2 emissions, raw material usage, energy consumption, waste generation, manufacturing energy, cost, and sustainability score.

The program's code was written in Python. While pandas and NumPy handled data processing,

PySimpleGUI was used to develop the graphical interface. Machine learning models were constructed using scikit-learn, and Matplotlib was used to create the graphics. Running the green supply chain mapper.py file launches the program. Once the interface is open, the user may choose the folder to output to and the CSV file to enter. The command `pip install pandas, numpy, matplotlib,`

scikit-learn, and PySimpleGUI will install all the necessary libraries like: pandas, numpy, matplotlib, scikit-learn, PySimpleGUI.

Figure 1 shows the experimental graphical user interface. The user may choose an input dataset, specify an output location, preview the columns, set up positive and negative indications, and then begin the analysis.

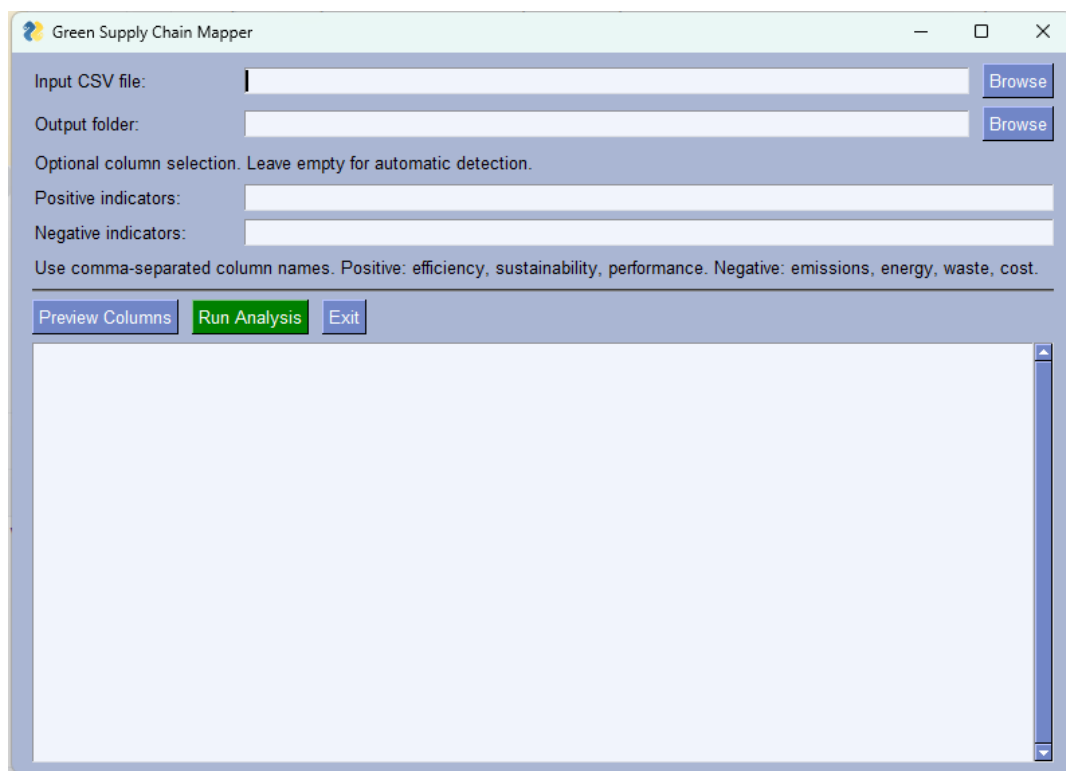


Figure 1 – *Application GUI*

The scoring stage was based on two types of indicators. The positive indicators were Sustainability_Score and Renewable_Energy_%, because higher values indicate a better green profile. The negative indicators were CO2_Emissions_kg, Raw_Material_Usage_kg, Energy_Consumption_kWh, Waste_Generated_kg, Manufacturing_Energy_kWh, and Cost_\$, because higher values indicate a higher environmental or operational burden.

The final score was computed after normalizing all relevant indicators. Immediately after normalization, positive signs were used. The end result was improved due to decreased emissions,

resource usage, energy consumption, waste, and expense as a consequence of inverting negative indicators following normalization. The total green performance score, which ranges from zero to one hundred, is the sum of all the normalized components.

Scores were then used to categorize the situations into three levels: low, medium, and high green performance. Thresholds based on percentiles were used to establish boundaries across classes. Instead of using fixed, arbitrary limitations, the categorization became dataset dependent.

The targeted variable in the machine learning step was the produced class. Instead of trying to forecast an external sustainability label, we wanted to see how well the indicators we chose might mimic the management-oriented categorization. Making use of a stable random state to ensure repeatability, the dataset was divided into 750 training examples and 250 testing cases. For this categorization, eleven characteristics were considered in total.

Five lightweight classifiers were compared: Naive Bayes, Decision Tree, Linear SVM, Logistic Regression, and kNN with $k = 3$. These models were selected because they are easy to reproduce and suitable for a practical comparative framework. For each classifier, the application computed the accuracy on the test set and generated a classification report and a confusion matrix.

The application exported several files for verification and interpretation. The main output files were `green_supply_chain_results.csv`, `green_supply_chain_ranking.csv`, `classifier_results.csv`, `analysis_summary.csv`, `selected_features.csv`, and `score_components.csv`. The first file stores the original records together with the computed score and the assigned class. The ranking file orders the scenarios from the highest to the lowest green performance score. The classifier file stores the accuracy values for all tested models.

At the machine learning step, the goal variable was the created class. Predicting an external sustainability label was not the goal; rather, it was to determine how well the chosen indicators replicate the management-oriented categorization. A fixed random state was used to partition the dataset into 750 training examples and 250 testing cases, ensuring repeatability. Eleven characteristics were considered for the categorization.

A straightforward and repeatable approach is provided by this technique. To compare machine learning classifiers, the user begins with a publicly available CSV dataset, picks the appropriate indications, gets a green performance score. You may use the outputs for management meetings, charts, and tables.

Results and discussion

The results produced by the application that was put into action are detailed in this section. The green supply chain dataset 1000.csv file was used for the analysis, with the positive and negative indications indicated in the methodology section. Confusion matrices, graphic figures, categorization reports, and CSV files were all output by the program. Prior to delving into the specific results, the overall procedure of the experiment is reviewed. In Table 1 you can see the most important numbers (Table 1).

Table 1 - General analysis setup

Indicator	Value
Input file	green_supply_chain_dataset_1000.csv
Number of records	1000
Number of original columns	12
Features used for machine learning	11
Training cases	750
Testing cases	250
Best classifier	Logistic Regression / Linear SVM
Best accuracy	0.968

(Source: processing based on Kaggle Ziya07, 2025).

The `green_supply_chain_results.csv` file was the first significant output; it contains the initial data, the calculated green performance score, and the performance class that was allocated. The

`green_supply_chain_ranking.csv` file was the second significant result. It lists all the scenarios in descending order of importance. The user may review the findings and choose the top supply

chain scenarios with the help of these files. The optimal green supply chain scenarios, as determined by the score, are shown in Figure 2.

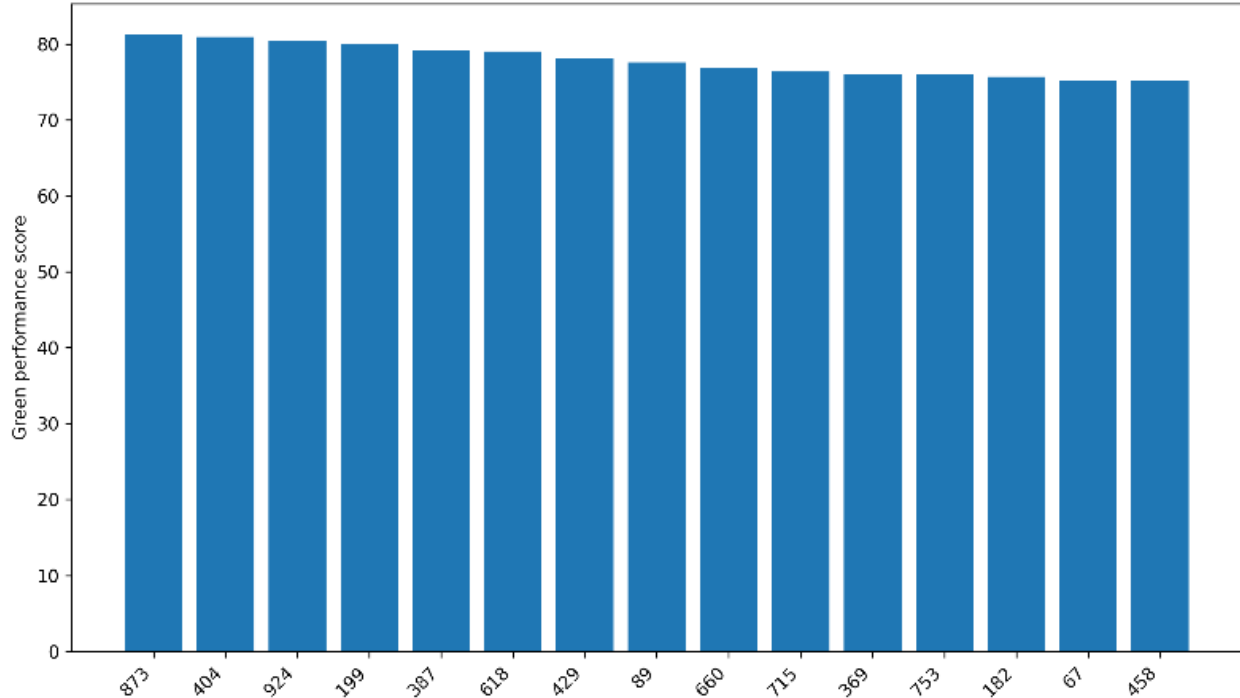


Figure 2 – Top green supply chain scenarios

(Source: representation after Kaggle Ziya07, 2025)

Scenario 873 had the best performance in the dataset that was evaluated, with a score of around 81.24. Scenario 387, situations 404 and 924 followed. The ranking should be seen as a shortlist

of strong possibilities rather than a fixed order, as many situations are close in value. To make the rating simpler to interpret, Table 2 presents the top five situations.

Table 2 - Top five green supply chain scenarios

Rank	Scenario ID	Product type	Green performance score
1	873	Electronics	81.24
2	404	Food	80.95
3	924	Food	80.37
4	199	Food	80.08
5	387	Apparel	79.20

(Source: ranking based on Kaggle Ziya07, 2025)

From a management point of view, these scenarios can be treated as the first alternatives to analyze. Not all indicators need to be in perfect order to get a high green performance score. It indicates that, compared to other instances, there is a better overall balance between cost,

sustainability, renewable energy, emissions, resource usage, waste, and energy consumption. In addition, the program categorized the one thousand possible outcomes into three eco-friendly performance levels. In Figure 3, you can see this distribution.

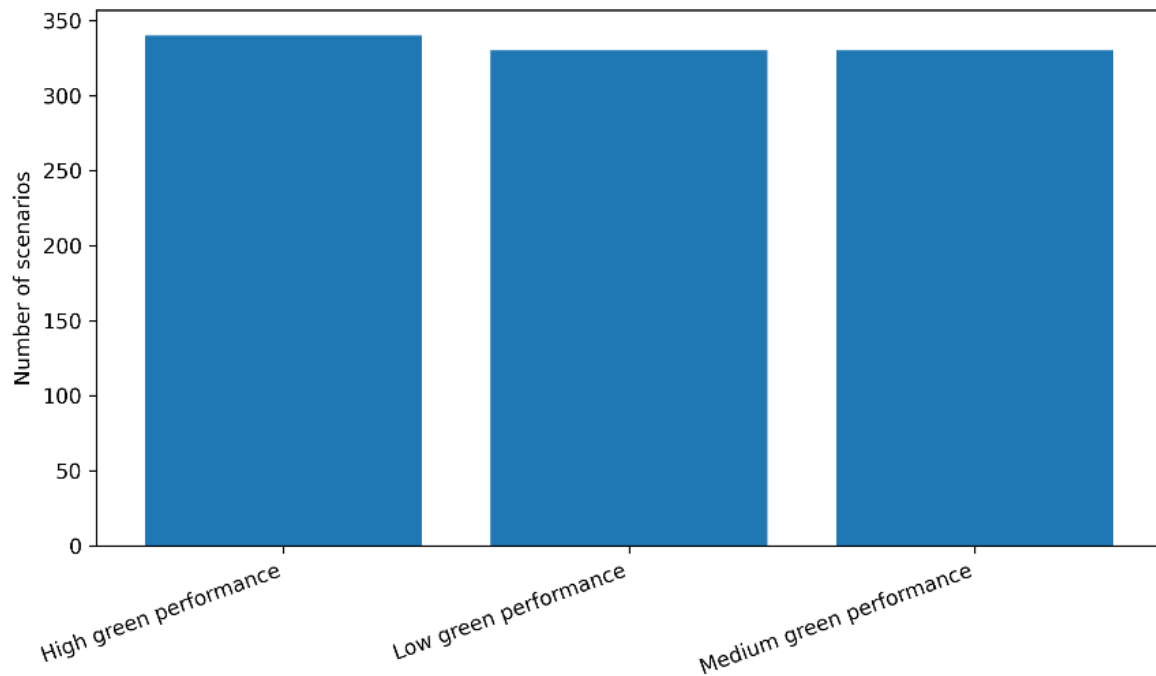


Figure 3 – *Distribution of green performance classes*

(Source: representation based on Kaggle Ziya07, 2025)

Almost all of the classes are evenly distributed. Three hundred and forty-three scenarios ranging from very low to medium levels of environmental impact are included in the

dataset. None of the classes take over the study, which is why the balance is helpful. The precise count of situations for each class is shown in Table 3.

Table 3 – *Distribution of green performance classes*

Green performance class	Number of scenarios
High green performance	340
Low green performance	330
Medium green performance	330
Total	1000

(Source: classification based on Kaggle Ziya07, 2025)

A basic summary of the dataset is provided by this outcome. A third of the situations fall into the „strong green” category, another third fall somewhere in the center, and a third have poorer green performance. This helps managers out as it

divides the dataset into several categories for making decisions. Through a comparison of their normalized indicator values, Figure 4 provides a more comprehensive look at the top possibilities.

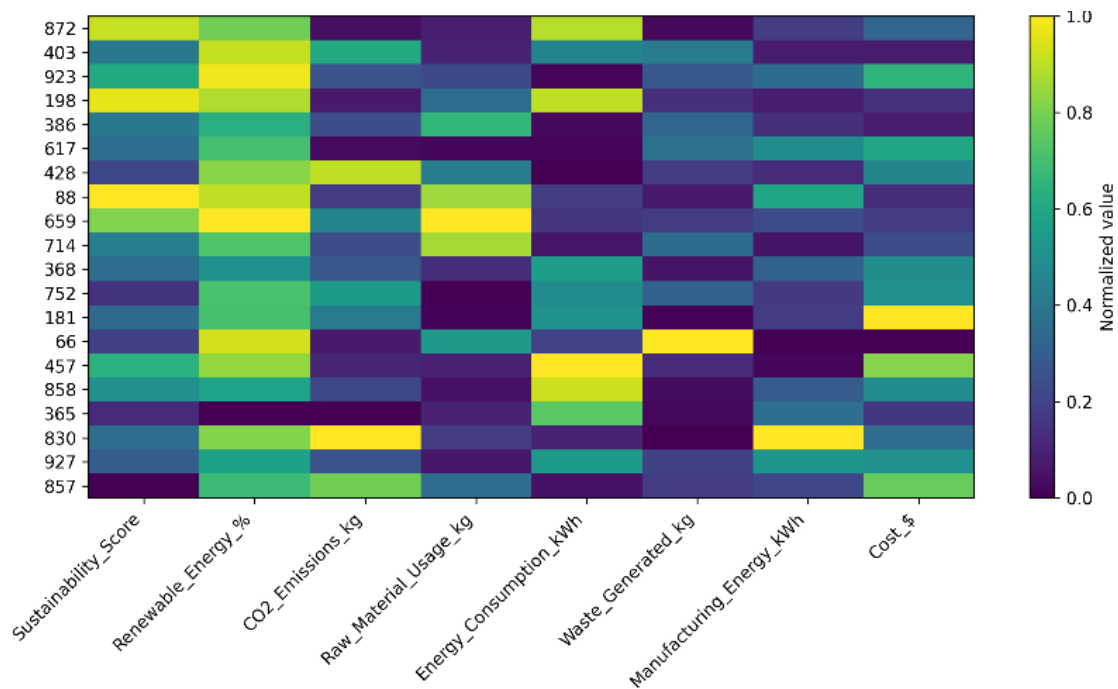


Figure 4 – Indicator heatmap for top scenarios

(Source: heatmap based on Kaggle Ziya07, 2025)

The heatmap clearly demonstrates that the top scenarios differ in profile. When it comes to renewable energy and sustainability, certain situations are quite valuable. Some do better than others because to their reduced cost, energy usage, waste, or pollution. This demonstrates that there is more than one technique to enhance green supply chain performance, which is helpful.

Five classifiers were evaluated in the machine learning stage. A total of 250 examples were used for testing after the models were trained on 750. The composite score's green performance class served as the dependent variable of interest. Figure 5 displays the results of each classifier's accuracy.

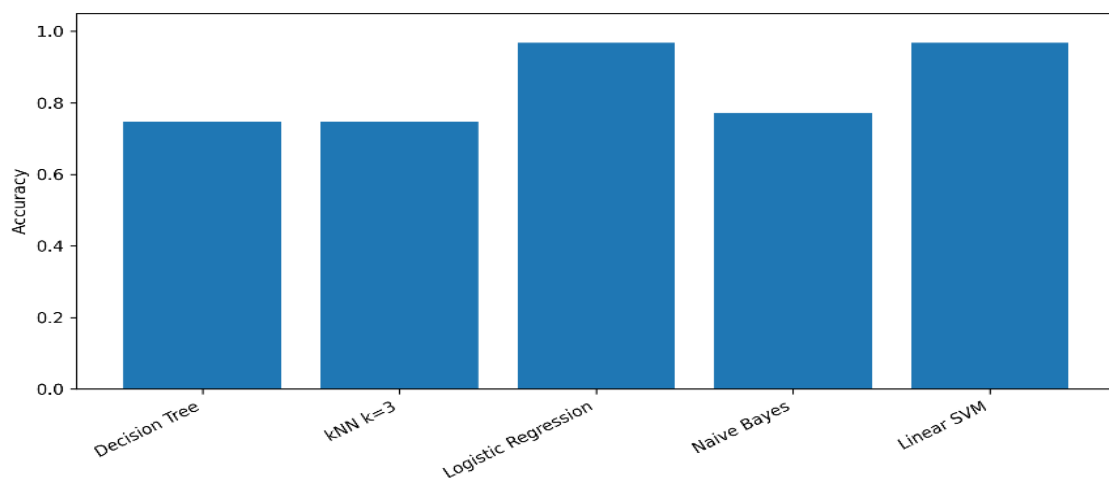


Figure 5 – Classifier comparison
(Source: results based on Kaggle Ziya07, 2025)

Logistic Regression and Linear Support Vector Machines produced the most favorable outcomes. The accuracy that the models achieved was 0.968. This proves that the chosen indicators

are capable of reliably recreating the green performance classes. Table 4 displays the accuracy values of all the classifiers that were evaluated.

Table 4 – Classifier comparison statistics

Model	Accuracy	Train size	Test size
Decision Tree	0.748	750	250
kNN k=3	0.748	750	250
Logistic Regression	0.968	750	250
Naive Bayes	0.772	750	250
Linear SVM	0.968	750	250

(Source: Authors' own machine learning results, based on Kaggle by Ziya07 (2025)).

The linear classifiers stand out from the rest of the models in the findings. Optimal results were achieved via Logistic Regression and Linear SVM. Accuracy was 0.748 for Decision Tree and kNN and 0.772 for Naive Bayes. Although these

numbers are within acceptable ranges, they fall short of the two top models. In Table 5, we can see the results for each class produced by the top two classifiers.

Table 5 – Detailed results for the two best classifiers

Model	Class	Precision	Recall	F1-score
Logistic Regression	High green performance	0.99	0.99	0.99
Logistic Regression	Low green performance	0.93	1.00	0.97
Logistic Regression	Medium green performance	0.99	0.91	0.95
Linear SVM	High green performance	0.98	0.99	0.98
Linear SVM	Low green performance	0.94	1.00	0.97
Linear SVM	Medium green performance	0.99	0.91	0.95

(Source: results, based on Kaggle Ziya07 (2025)).

The detailed values confirm that both models classified the three groups very well. The Medium green performance class was slightly more difficult to separate. This is expected, because medium scenarios are placed between the low and high groups and may share characteristics with both.

You shouldn't take the outcomes as definitive, automatic judgments, but rather as results to help you make a decision. Using the equal-weight scoring system and the indicators chosen determine the green performance score. Although the rankings and classes may help managers find better scenarios, other factors such as supplier

dependability, product quality, delivery risk, market demand, and long-term corporate strategy may also play a role in the ultimate selection.

There were obvious results for environmentally conscious supply chain management from the application as a whole. It created figures for visual interpretation, graded the situations, and compared machine learning classifiers. It also classified them into performance groups. The results show that a simple Python-based framework can transform a public supply chain dataset into practical information for green business model analysis.

Conclusions

This paper presented a Python-based application for analyzing green supply chain scenarios with simple machine learning methods. The application was developed as a standalone tool with a graphical interface, so the user can load a CSV file, select the relevant indicators, run the analysis, and obtain tables and figures without changing the source code.

The proposed workflow was tested on the file `green_supply_chain_dataset_1000.csv`, which contains 1000 supply chain scenarios. The application used sustainability and renewable energy as positive indicators, while emissions, raw material use, energy consumption, waste, manufacturing energy, and cost were treated as negative indicators. Based on these variables, the tool computed a green performance score for each scenario and assigned the scenarios to three classes: low, medium, and high green performance.

According to the findings, the software can determine which green supply chain scenarios are the most favorable and then rate them. All of the scenarios were very close to the best scenario's green performance score of about 81.24. So, don't rely on the rating as a final, automatic conclusion; utilize it to create a shortlist for more research.

There was some use in the class distribution for managerial interpretation as well. With 340 high-green performance situations, 330 medium-green performance scenarios, and 330 low-green

performance scenarios, the dataset was almost equally distributed across the three performance categories. By doing so, we can see the big picture of the dataset and identify which situations are stronger and which ones may need some work.

With a combined accuracy of 0.968, Logistic Regression and Linear Support Vector Machines were determined to be the top classifiers. These results show that the chosen indicators are capable of producing highly accurate replicas of the created green performance classes. Although their results were lower, Decision Tree, kNN, and Naive Bayes served as good benchmarks inside the application.

The suggested tool is mostly useful for practical purposes. It provides a framework for managers to compare green supply chain scenarios, but it does not replace management judgment. Classifier findings, rankings, heatmaps, and exported CSV files may bolster talks about operational decisions, costs, emissions, energy use, and sustainability.

There are limitations to the present version as well. Equivalent weights provide the basis of the green performance score, which is used to generate performance classes from the dataset that has been evaluated. Users may contribute their own weights to the tool, and it can be enhanced with more sustainability metrics, more datasets, and better decision-support approaches in future development. The program demonstrates that even in its present state, a basic Python framework may facilitate green business model analysis by producing observable and repeatable results.

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Robotic Process Automation an Enabler of Green Business Models

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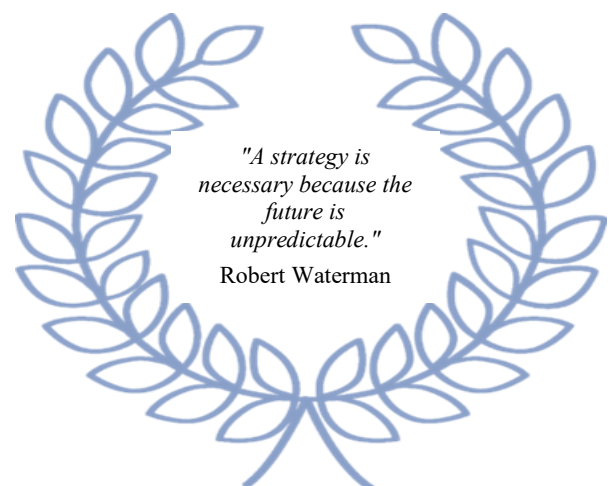
Abstract

This conceptual article examines how digital accounting, robotic process automation (RPA) and artificial intelligence (AI) can support the transition of Romanian SMEs towards green business models. The paper develops an integrative framework, named the Digital Green Accounting Loop, that shows how fiscal and accounting data can be captured by RPA, enriched by AI-based classification and anomaly detection, translated into environmental and managerial indicators, and used for green value proposition, green operations, sustainable finance and voluntary sustainability reporting. The contribution is twofold. First, it links digital compliance data with green business model innovation, an underexplored issue in Romanian SME research. Second, it proposes practical governance conditions for SMEs: data quality, human oversight, cyber-security, proportional sustainability metrics and gradual implementation.

Keywords: digital accounting, green business models, robotic process automation

Introduction

The debate on green business models has moved from a peripheral sustainability topic to a central managerial concern. Companies are increasingly expected to demonstrate how they create value while reducing negative environmental impacts, using resources more efficiently and responding to the information needs of customers, financiers and public authorities. For small and medium-sized enterprises (SMEs), this transition is particularly difficult. They are close to markets and supply chains, but they usually have fewer financial, technological and human resources than large corporations. Consequently, a green business model cannot be reduced to a declaration of environmental intentions; it requires data, measurement routines and managerial processes that make environmental performance visible and actionable.



This article approaches green business models from the perspective of accounting digitalisation. The central premise is that digital accounting can become an enabling infrastructure for green business model innovation. The Romanian case is

relevant because, during 2024-2026, SMEs have been exposed to an accelerated process of fiscal digitalization: electronic invoicing, SAF-T/D406 reporting (Standard Audit File for Tax), electronic transport monitoring and other systems have gradually transformed tax compliance into a data-intensive process. The research is positioned at the intersection of digital accounting, RPA, AI and the economic-financial activity of Romanian SMEs, with the core idea that digital fiscal compliance can be transformed from a legal obligation into an operational and strategic advantage.

The connection with green business models is not only theoretical. Sustainability reporting requirements are changing across Europe, and SMEs are increasingly asked for environmental, social and governance information by banks, large customers, public procurement systems and supply-chain partners. The voluntary sustainability reporting standard for non-listed SMEs (VSME) developed by EFRAG (European Financial Reporting Group) and presented by the European Commission is designed to reduce the reporting burden while helping SMEs respond to sustainability information requests and improve access to finance. At the same time, OECD work on SME sustainability reporting highlights that environmental data can become useful for finance, supply-chain integration, resource efficiency and regulatory alignment, but many SMEs lack the tools and expertise needed to collect it.

The article therefore asks how structured accounting and fiscal data can be re-used for green management purposes. If RPA can capture, validate and archive repetitive data flows, and AI can classify, detect anomalies and support forecasting, then accounting systems can become more than compliance instruments. They can provide a basis for monitoring energy-related costs, supplier behaviour, logistics patterns, resource consumption proxies and cash-flow effects of green investments. This does not mean that fiscal data alone is sufficient for complete environmental accounting. Rather, it suggests that digital accounting can provide the backbone on which proportional green metrics and decision routines can be built.

The research questions are: RQ1: How can digital accounting and fiscal compliance data support the development of green business models in Romanian SMEs? RQ2: Which RPA and AI functions are most relevant for translating accounting data into green managerial indicators? RQ3: What governance conditions are required to prevent digitalization from becoming either a new administrative burden or a source of uncontrolled technological risk? The remainder of the paper is structured as follows. Section 2 reviews the literature and the Romanian context. Section 3 explains the methodology. Section 4 presents the proposed Digital Green Accounting Loop and discusses its implications. Section 5 concludes (Figure 1).

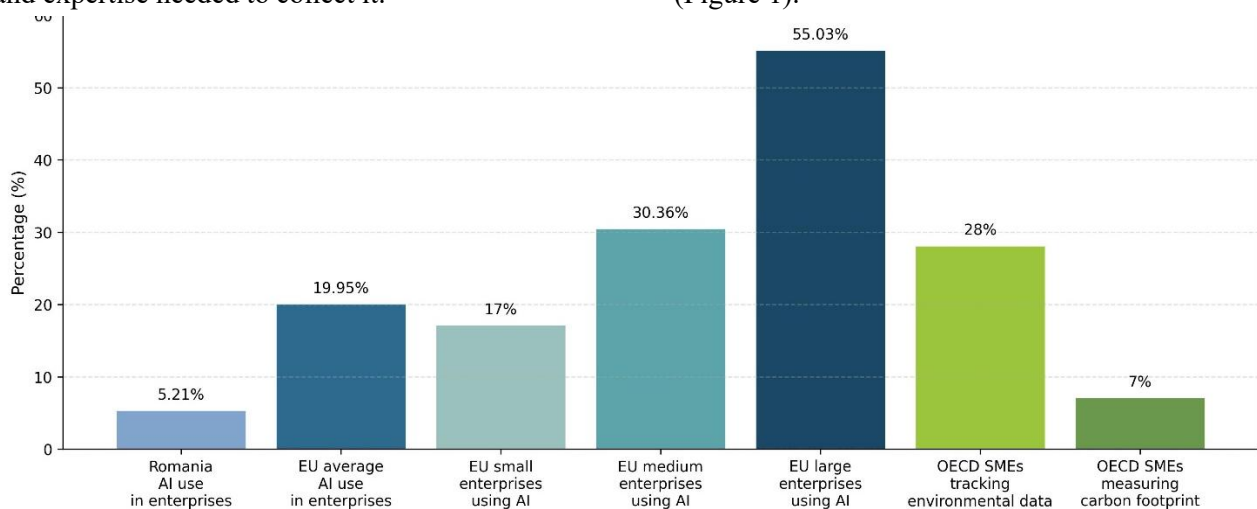


Figure 1 - Context indicators for the digital and green transition of SMEs
(Source: compilation based on Eurostat (2025), and Bianchini and Lasheras Sancho (2025))

Literature background

Green business models and SME sustainability reporting. A business model describes how an organization creates, delivers and captures value. In the sustainability literature, the concept has been extended to include not only economic value, but also environmental and social value. Sustainable business model archetypes include maximising material and energy efficiency, creating value from waste, substituting with renewables and natural processes, delivering functionality rather than ownership, adopting stewardship roles and encouraging sufficiency (Bocken et al., 2014). Sustainable business model innovation is therefore not a simple marketing repositioning; it modifies the logic of value proposition, value creation and value capture (Boons and Lüdeke-Freund, 2013; Geissdoerfer et al., 2018).

For SMEs, the practical difficulty is that green business model innovation requires data that is often not collected in a systematic way. An SME may know the value of purchased electricity, fuel, packaging or logistics services, but it may not know the environmental meaning of these transactions or their impact on customer relationships, bank financing or supply-chain requirements. This gap is visible in recent international SME evidence: the OECD D4SME survey shows that only a minority of SMEs track environmental data, and even fewer measure carbon-footprint information. The problem is not necessarily a lack of goodwill; it is the absence of simple, low-cost, process-based data routines.

The European VSME initiative (a Voluntary Standard for Micro, small and medium-sized Enterprises) outside the scope of mandatory corporate sustainability reporting, intended to help them answer sustainability data requests, improve sustainability management and access sustainable finance. The European Commission has also presented a voluntary sustainability reporting standard to ease the burden on SMEs, acknowledging that many SMEs face information requests from large companies and financial

institutions even when they are not directly subject to mandatory reporting. This makes the link between accounting information systems and sustainability reporting increasingly important.

Digital accounting, RPA and AI as accounting infrastructure. Digital transformation is broader than the conversion of paper documents into electronic files. It refers to organizational change enabled by digital technologies, affecting processes, roles, capabilities and value creation (Vial, 2019; Verhoef et al., 2021). In accounting, this distinction is crucial. A PDF invoice stored in a folder is only digitised information; an invoice transmitted as structured data, automatically validated, connected with bank payments and used for managerial analysis is part of a digital process. This shift is the basis for digital green accounting.

RPA is particularly suited to accounting because many accounting processes are repetitive, rule-based and dependent on interactions between information systems. Prior research on RPA in accounting highlights its capacity to automate standardised tasks such as data extraction, reconciliation, report generation and transaction processing (Kokina and Blanchette, 2019; Cooper et al., 2019). However, RPA creates value only when processes are stable and rules are well documented. A robot that repeats an incorrect rule will multiply errors faster than a human operator. For green business models, RPA is useful at the data-capture layer: it can collect invoices, bank data, supplier data and structured reports needed for green indicators.

AI adds a different capability. Instead of merely executing predefined steps, AI can classify transactions, detect unusual patterns, learn from historical corrections and support forecasts. In managerial accounting, these capabilities can improve the timeliness and analytical value of information, but they also introduce ethical and governance risks related to transparency, privacy, responsibility and trust (Zhang et al., 2023). In a green business model context, AI can support the classification of expenses relevant to energy, logistics, materials or waste; identify anomalies in resource-related costs; or simulate cash-flow effects

of green investments. AI should therefore be treated as decision support, not as a substitute for professional judgement.

The Romanian context. Romania offers a specific context in which fiscal digitalisation is a strong institutional driver of accounting transformation. RO e-Factura has generalised electronic invoicing and requires firms to handle structured XML invoice data, while SAF-T/D406 requires the export of accounting, tax and inventory-related data in a standardised format. For small taxpayers, the obligation to submit SAF-T started on 1 January 2025. The effect is that even firms with limited resources must improve the consistency of their accounting data, product and partner nomenclatures, tax codes and reconciliation routines.

At the same time, Romania displays a significant digital gap. Eurostat reported that in 2025 only 5.21% of Romanian enterprises with at least 10 employees used AI technologies, compared with

19.95% in the European Union. The Digital Decade country report for Romania also emphasises the need to increase digital skills in the private sector and to boost SME digital capabilities. This means that Romanian SMEs are simultaneously pushed into digital fiscal compliance and held back by limited skills, fragmented systems and low AI adoption.

The green dimension is also becoming more concrete. The Romanian Sustainability Code is designed as a tool for transparent reporting on companies' impact on sustainable development, and it is meant to support both mandatory and voluntary reporting. For SMEs, this creates a practical challenge: sustainability reporting should not become a second, disconnected administrative layer. A more feasible approach is to connect green indicators to existing accounting and operational data, using digital accounting systems as the base infrastructure (Table 1).

Table 1 - Conceptual integration used in the article

Concept	Core meaning in the literature	Role in this article	Main sources
Green business model	A model that integrates environmental value into value proposition, creation, delivery and capture.	Outcome to be enabled by accounting data, green KPIs and managerial decisions.	Bocken et al., 2014; Boons and Luedeke-Freund, 2013; Geissdoerfer, Vladimirova and Evans, 2018
Digital accounting	Accounting processes redesigned through structured data, integration and digital workflows.	Data backbone for green measurement and sustainability-related decisions.	Vial, 2019; Verhoef et al., 2021; Moll and Yigitbasioglu 2019
RPA	Software robots executing repetitive, rule-based tasks across information systems.	Data capture, validation, archiving and routine reconciliation.	Kokina and Blanchette, 2019; Cooper et al., 2019
AI	Models that classify, detect patterns, generate predictions or support decisions.	Green transaction tagging, anomaly detection, forecasting and scenario support.	Eurostat, 2025; Zhang et al., 2023
VSME and SME sustainability reporting	Proportional sustainability reporting for SMEs outside the mandatory CSRD scope.	Reporting destination and stakeholder communication layer for green accounting data.	EFRAG, 2025a; European Commission, 2025a; OECD, 2025b

Methodology of research

The paper uses a conceptual research design based on an integrative literature review and framework development. This design is appropriate because the topic combines several research streams that are often analyzed separately: green business models, sustainability reporting for SMEs, accounting digitalization, RPA, AI and Romanian fiscal digitalization. The objective is not to test causal relationships with primary survey data, but to build a coherent framework that can later be empirically validated in Romanian SMEs.

The review included three categories of sources. The first category consists of academic studies on sustainable and green business models, digital transformation and accounting technologies, including articles from Journal of Cleaner Production, Journal of Business Research, The British Accounting Review, International Journal of Accounting Information Systems and Accounting Horizons. The second category consists of official European, OECD and Romanian sources regarding SME sustainability reporting, AI adoption, digital skills, VSME, RO e-Factura, SAF-T and the Romanian Sustainability Code. The third category consists of the author's ongoing doctoral research direction on the impact of RPA and AI on the economic-financial activity of Romanian SMEs.

The analytical procedure followed four steps. First, the main concepts were delimited: green business model, digital accounting, RPA, AI and proportional SME sustainability reporting. Second, current contextual data were extracted from official sources to identify the Romanian relevance of the problem. Third, accounting processes were mapped according to their ability to generate environmental and managerial information. Fourth, a conceptual framework was designed to show how structured accounting data can travel from fiscal compliance to green business model decisions.

Because the article is conceptual, its validity is based on theoretical consistency, practical plausibility and triangulation across sources rather than on statistical inference. The framework is designed for future empirical testing through surveys, interviews and case studies with Romanian

SMEs and accounting professionals. Future research may measure whether SMEs that integrate RPA/AI into accounting processes also report better data quality, more frequent green KPI monitoring and stronger green business model orientation.

Results and Discussion

From digital fiscal compliance to green accounting data infrastructure. The first result of the conceptual analysis is that fiscal digitalization can be interpreted as a data infrastructure rather than only as a compliance obligation. In traditional accounting, invoices, bank extracts, receipts and declarations often remain fragmented across documents and systems. In digital accounting, these elements can be transformed into structured data flows. RO e-Factura provides structured invoice data; SAF-T imposes consistency across accounting, tax and inventory records; bank integrations allow faster reconciliation; ERP systems can connect transactions with products, projects or cost centres.

This infrastructure is relevant for green business models because many environmental impacts are reflected, directly or indirectly, in economic transactions. Energy costs, fuel, packaging, raw materials, waste-management services, maintenance, logistics and green investments all leave accounting traces. These accounting traces do not automatically become environmental indicators, but they can be used as starting points. For example, electricity invoices can be connected with energy consumption and cost per unit of output; logistics invoices can be connected with delivery routes and transport choices; supplier invoices can be connected with green procurement criteria.

The reuse of accounting data is also consistent with the principle of proportionality for SMEs. Instead of asking SMEs to build complex sustainability reporting departments, a digital green accounting approach begins with data that SMEs already collect for fiscal and financial reasons. The challenge is to add a green interpretation layer to the accounting data, using RPA for data capture and AI for classification and anomaly detection.

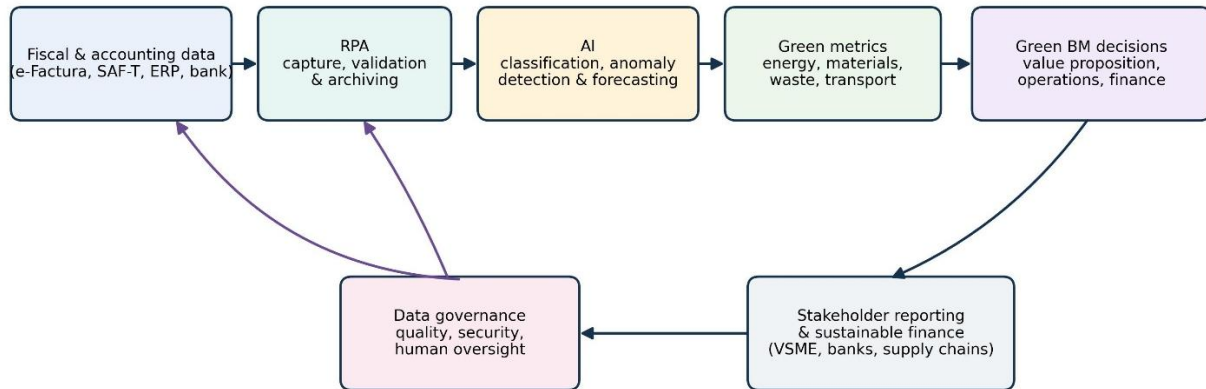


Figure 2 - Digital Green Accounting Loop (DGAL)

(Source: developed by integrating Bocken et al. (2014), Kokina and Blanchette (2019), Moll and Yigitbasioglu (2019), Zhang et al. (2023), and EFRAG (2024).

The Digital Green Accounting Loop. The proposed framework is named the Digital Green Accounting Loop (DGAL). The term “loop” is used because green accounting data should not stop at reporting. It should return to managerial decisions, process redesign and data governance. The first component of the loop is the digital fiscal and accounting data layer. This layer includes e-invoices, SAF-T data, ERP records, bank data, payroll data where relevant, stock records and logistics-related documents. The second component is the RPA layer, where repetitive operations are automated: downloading documents, validating mandatory fields, identifying duplicates, archiving files, importing data and generating exception lists.

The third component is the AI layer. AI can assign transactions to green categories, detect unusual consumption patterns, estimate future cash-flow consequences of green investments and support scenario analysis. For example, if fuel costs increase disproportionately relative to sales volume, AI may flag a logistics inefficiency that requires managerial investigation. If energy costs per unit of output decrease after equipment modernization, the accounting system can support both financial and environmental interpretation.

The fourth component is the green accounting metrics layer. This layer translates transactions into a limited set of indicators that are relevant for SMEs: energy cost intensity, material efficiency, waste-management costs, share of green suppliers, transport-related cost intensity, investment in cleaner technologies and estimated emissions proxies where precise emissions data are not available. These indicators should be proportional, auditable and easy to understand. They should not overburden SMEs with excessive complexity. (Figure 2).

The fifth component is the green business model decision layer. Here, accounting information supports decisions about value proposition, operations and value capture. A firm may reposition products as lower-waste alternatives, redesign packaging, select suppliers based on environmental criteria, optimize routes, introduce repair or reuse services, or seek green financing. The final component is stakeholder reporting and feedback. The same data can support voluntary VSME reporting, bank questionnaires, supplier scorecards and internal sustainability dashboards. The loop is closed when reporting feedback leads to improved data governance and process refinement (Table 2).

Table 2 - *From digital accounting data to green business model decisions*

Accounting / fiscal data source	RPA function	AI function	Green indicator supported	Business model decision
RO e-Factura supplier invoices	Download, archive, duplicate check, VAT and supplier validation	Classify energy, packaging, logistics and waste-related expenses	Green cost categories; supplier-related environmental data	Green procurement and supplier selection
SAF-T / ERP accounting and inventory data	Extract standard data and reconcile modules	Identify inconsistencies and abnormal consumption patterns	Material efficiency; stock losses; resource intensity	Process redesign and circularity initiatives
Bank statements and receivables/payables	Automated reconciliation and ageing lists	Forecast cash-flow impact of green investments	Financial feasibility of sustainability projects	Green investment timing and financing needs
Transport-related documents and invoices	Collect transport costs and match them with customers/products	Detect route/cost anomalies and delivery inefficiencies	Transport cost intensity; logistics proxy indicators	Low-emission logistics, route optimisation and customer policies
Management reports and dashboards	Generate recurring KPI reports	Scenario analysis and alerts	Energy, materials and cash-flow dashboards	Green value proposition and performance monitoring

(Source: based on Bocken et al. (2014); Geissdoerfer et al., (2018); Kokina and Blanchette (2019); Cooper et al. (2019); Moll and Yigitbasioglu (2019); Zhang et al. (2023); Bianchini and Lasheras Sancho (2025); and EFRAG (2024)).

Implications for the components of green business models. The framework has implications for the three classical components of a business model: value proposition, value creation and delivery, and value capture. At the value proposition level, digital green accounting can help SMEs substantiate environmental claims. A company should not simply state that it is “green”; it should be able to show how resource use, packaging, logistics or supplier choices have changed. Accounting data can provide the internal evidence needed to support more credible market communication.

At the value creation and delivery level, RPA and AI can identify operational inefficiencies that are both financial and environmental. High energy costs, waste-management costs or logistics costs are not only accounting expenses; they may reveal process inefficiencies or opportunities for redesign. For example, a production SME may use data to identify material losses, while a distribution SME

may use transport invoices and route data to improve logistics. In this sense, green business model innovation is linked to operational accounting intelligence.

At the value capture level, the link with sustainable finance is important. Banks and investors increasingly request sustainability-related information. A Romanian SME that can produce basic, coherent and reliable green metrics is better positioned to answer financing questionnaires, participate in green supply chains and demonstrate resilience. This does not guarantee financing, but it reduces the information asymmetry between SMEs and external stakeholders.

A further implication concerns the role of the accountant. The accountant becomes a mediator between fiscal compliance, digital systems and sustainability management. Instead of only recording documents, the accountant can define data rules, validate AI classifications, interpret green cost indicators and explain the financial

impact of environmental initiatives. This extends the professional role without eliminating the need for human judgement.

A staged maturity pathway for Romanian SMEs. Romanian SMEs should not be expected to move directly from manual accounting to AI-driven sustainability analytics. A staged approach is more realistic. At the first stage, the firm treats digital fiscal systems as compliance obligations. At the second stage, the firm automates repetitive accounting processes through RPA and improves data quality. At the third stage, the firm adds a green KPI layer to existing accounting categories. At the

fourth stage, AI is introduced for classification, anomaly detection and forecasting. At the fifth stage, the firm redesigns business model components based on the information generated by the system.

This staged pathway is important because it protects SMEs from two opposite risks. The first risk is technological minimalism: doing only what is legally required and missing the managerial value of digital data. The second risk is technological overreach: buying complex AI solutions before processes, data and governance are mature. A staged approach allows SMEs to match ambition with capacity (Figure 3).

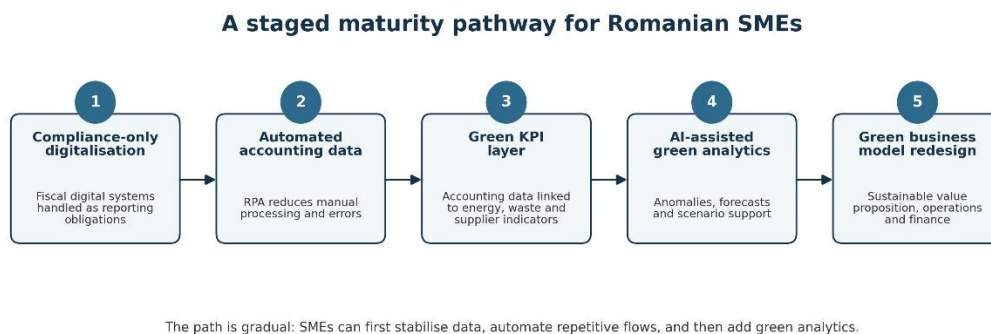


Figure 3 - Maturity pathway from compliance digitalization to green business model redesign

(Source: based on Vial (2019), Verhoef et al. (2021), Kokina and Blanchette (2019), Zhang et al. (2023), Geissdoerfer et al. (2018).

Risks and governance conditions. Digitalization is not automatically green. Digital systems consume energy, require hardware, generate cyber-security exposure and may create dependency on software providers. AI systems may produce inaccurate classifications or recommendations that appear plausible but are wrong. In accounting, these risks are material because errors may affect tax compliance, financial statements, management decisions and sustainability claims.

The governance of digital green accounting should therefore include at least six conditions. First, data quality must be managed through clear

nomenclatures, supplier records, product categories, tax codes and cost centres. Second, RPA rules must be documented, tested and periodically reviewed. Third, AI outputs must be subject to human validation, especially when they influence reporting or strategic decisions. Fourth, cyber-security controls such as multi-factor authentication, limited access rights, backups and audit logs are necessary. Fifth, sustainability metrics should be proportional and explainable. Sixth, SMEs should monitor the environmental footprint of digital solutions themselves, avoiding the paradox of using technology to support sustainability while ignoring technology-related impacts (Table 3).

Table 3 - Governance risks and controls for digital green accounting

Risk	Possible manifestation	Effect on green business model	Control mechanism
Poor data quality	Duplicate suppliers, wrong product codes, inconsistent cost centres	Green KPIs become unreliable	Data owners, validation rules, periodic cleansing
RPA rule error	Robot processes many documents using a wrong rule	False cost or environmental interpretation	Pilot testing, exception lists, accountant approval
AI misclassification	Expenses wrongly tagged as energy, waste or logistics	Misleading sustainability reporting or decisions	Human oversight, confidence thresholds, audit trails
Cyber-security and privacy	Unauthorised access to invoices, bank data or employee data	Loss of trust and operational disruption	Limited rights, MFA, backups, access logs
Technology footprint	High energy use of systems, hardware replacement, e-waste	Digital solution undermines green narrative	Cloud/provider assessment and lifecycle thinking
Over-reporting burden	Too many indicators for SME capacity	Green model becomes administrative overload	Proportional metrics aligned with VSME and stakeholder needs

(Source: Vial (2019); Verhoef et al. (2021); Kokina and Blanchette (2019); Cooper et al. (2019); Zhang et al. (2023); Bianchini and Lasheras Sancho (2025); EFRAG (2024); and OECD (2025b)).

Research propositions for future empirical validation. The framework can be translated into several research propositions. P1: SMEs with higher levels of accounting digitalization are more likely to collect and use sustainability-related information. P2: RPA adoption in accounting processes improves the timeliness and reliability of data needed for green KPIs. P3: AI-assisted classification and anomaly detection increase the managerial usefulness of sustainability-related accounting information, provided that human validation is present. P4: The relationship between digital accounting and green business model innovation is mediated by data governance maturity. P5: External stakeholder pressure, especially from banks and supply-chain partners, strengthens the link between green accounting data and business model redesign.

These propositions can be tested in future research through a mixed-methods design. A survey of Romanian SMEs could measure digital maturity, RPA/AI adoption, green KPI use, sustainability

reporting exposure and green business model orientation. Interviews with accountants, managers and software providers could explain the mechanisms behind the quantitative relationships. Case studies could map actual invoice-to-KPI workflows in sectors such as distribution, professional services, production and transport.

Conclusions

This article has argued that digital accounting can become an enabling infrastructure for green business models in Romanian SMEs. The argument is grounded in the twin transition: SMEs must adapt simultaneously to digitalization and sustainability expectations. Romania's fiscal digitalization creates structured accounting data through electronic invoicing and SAF-T, while European sustainability developments such as VSME increase the need for proportional and reliable sustainability information. The challenge is to connect these developments instead of treating them as separate administrative burdens.

The main contribution of the article is the Digital Green Accounting Loop. The framework shows how fiscal and accounting data can be captured by RPA, enriched by AI, translated into green metrics and used for business model decisions. It also shows that governance is not optional. Data quality, human oversight, cyber-security, proportional indicators and gradual implementation are necessary conditions for transforming digital compliance into green value creation.

For managers, the article suggests that green business model innovation should start with data already available in accounting systems. For accountants, it suggests a broader professional role, moving from transaction processing to data governance, green KPI interpretation and managerial support. For researchers, it offers

propositions that can be tested empirically in Romanian SMEs.

The paper has limitations. It is conceptual and does not present primary empirical data. Some environmental impacts cannot be captured through accounting data alone and require technical measurements, supplier information or sector-specific methodologies. In addition, the Romanian regulatory and technological environment changes quickly, which means that the framework should be periodically updated. Future studies should validate the framework through surveys, interviews and case studies, and should examine whether digital green accounting improves not only reporting capacity, but also actual environmental and financial performance.

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