Integration of Green Digital Twins into Internal Control Systems through Bibliometric Analysis of Innovative Management Solutions Using Vosviewer

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Abstract

In a global business environment characterized by the climate crisis and accelerated digitalization, corporate governance and internal control are undergoing a profound structural transformation. This paper conducts a systematic review of the literature on the integration of advanced technology systems into sustainability management and internal control structures of organizations. The adopted methodology is based on a rigorous bibliometric analysis of scientific literature indexed in the Web of Science Core Collection, using VOSviewer software for structural, temporal, and keyword density mapping. The results indicate an exponential growth of academic interest, with a critical inflection point in 2022 and rapid technological maturation by 2026, evolving from simple data collection (IoT, Big Data) to autonomous predictive optimization based on artificial intelligence and deep learning. Categorical analysis demonstrates strong overlap between environmental sciences, information systems, and corporate governance. The density analysis also indicates a concentration of literature around governance concepts and ESG indicators, while aspects related to human capital, green finance or supply chain sustainability currently occupy peripheral positions in the research network.

Keywords: *green digital twins, internal control, bibliometric analysis, dynamic capabilities, ESG performance, artificial intelligence.*

JEL classification: Q56, O33, Q55.

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1. Introduction

In the current macroeconomic context, characterized by high volatility and the pressing need for organizations to meet global sustainability standards,

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governance systems are undergoing structural reconfiguration. The evolution of non-financial reporting legislation and the implementation of ESG (environmental, social, and governance) criteria require companies to adopt rigorous oversight mechanisms (Si, C., et al, 2025). Traditionally, internal control served the role of ensuring compliance with procedures, operational regularity, and financial risk management. However, expanding corporate responsibility toward a circular economy and carbon emission reduction requires the transformation of internal control into a tool capable of tracking diverse variables and complex environmental indicators. In parallel with the growing environmental imperative, the development of cyber-physical technologies offers new modeling and simulation architectures (Huang, X., et al, 2025, Cristache, N., & Cărăuș, A. L., 2024). Among these, digital twin systems have attracted increased attention due to their ability to reflect physical processes within an organization in real time. Although virtual models were initially used primarily in engineering and rigorous manufacturing processes, their potential integration into decision-making frameworks represents a complex, interdisciplinary research area, located at the intersection of computational science, environmental management, and corporate governance (Bugheanu, A. M., et al, 2026).

To understand the maturity of this field and how scientific literature addresses the convergence between digitalization and sustainability management, a structural assessment of the existing academic literature is necessary. The fragmentation of research and the diversity of methodological perspectives necessitate a systematic study that will clarify the trajectory of key concepts and theoretical foundations underpinning contemporary research (Cristache, N., et al, 2024).

With these premises in mind, the primary goal of this paper is to map, from a bibliometric perspective, the specialized literature devoted to the integration of intelligent systems and digital models into sustainability management and control frameworks (Năstase, M., et al, 2024, Fortea, C., et al, 2024). To achieve this overall goal, the study aims to address the following specific objectives:

- Determine the interdisciplinary profile of the field by quantitatively distributing publications across research categories established by the Web of Science platform.
- Identify the main thematic clusters and conceptual frameworks around which the scientific literature indexed in the Web of Science Core Collection revolves.
- Analyze the temporal dynamics of keywords to reveal the chronological evolution of terminology and research priorities in recent years.
- Assess the density of the bibliometric network to distinguish between well-established conceptual areas and low-frequency research niches.

By addressing these objectives, this article aims to provide a neutral and structured overview of the current scientific landscape, providing researchers and practitioners with a systematic documentary database on the state of knowledge in

the field of sustainable digital governance (Zlati, M. L., et al, 2026, Croitoru, G., et al, 2026).

2. Results and discussion

2.1 Methodology

To ensure a high level of scientific rigor and replicability of the results, the present research uses a quantitative approach based on bibliometric analysis of specialized literature. Data collection was carried out using the international database Web of Science Core Collection (WoS).

The search string used in the WoS interface was configured as follows: TS=(("digital twin*" OR "cyber-physical system*" OR "smart system*" OR "intelligent system*" OR "smart factory" OR "industry 4.0" OR "digital* transformation" OR "digitali*ation" OR "artificial intelligence" OR "AI" OR "big data" OR "predictive analytics" OR "virtual simulation*" OR "internet of things" OR "IoT") AND ("internal control*" OR "management control*" OR "governance" OR "internal audit*" OR "accounting" OR "managerial practice*" OR "risk management" OR "compliance" OR "accountability" OR "reporting system*" OR "oversight" OR "managerial tool*") AND ("sustainab*" OR "green*" OR "circular economy" OR "eco-efficiency" OR "environmental*" OR "carbon footprint" OR "ESG" OR "corporate social responsibility" OR "CSR" OR "clean* production")).

Following the database query, a robust sample of 10,401 results was extracted. The extracted metadata set was exported in a compatible format and processed using the specialized bibliometric analysis software VOSviewer (version 1.6.20). In total, 31,933 keywords were identified within the extracted sample, the minimum threshold for the appearance of a keyword within the sample was set to at least 20 times. Following the application of this filtering criterion, 504 keywords were selected, these constituting the final conceptual core subject to further analysis.

2.2 Analysis results

Figure 1. presents the distribution of works by category in the Web of Science Core Collection that confirms the deep interdisciplinary character and structural complexity of the investigated field. The quantitative supremacy of the ecological sphere, represented by Environmental Sciences (1902), Environmental Studies (1520) and Green Sustainable Science Technology (1514), demonstrates that the pillar of sustainability constitutes the ethical foundation and the final direction of research.

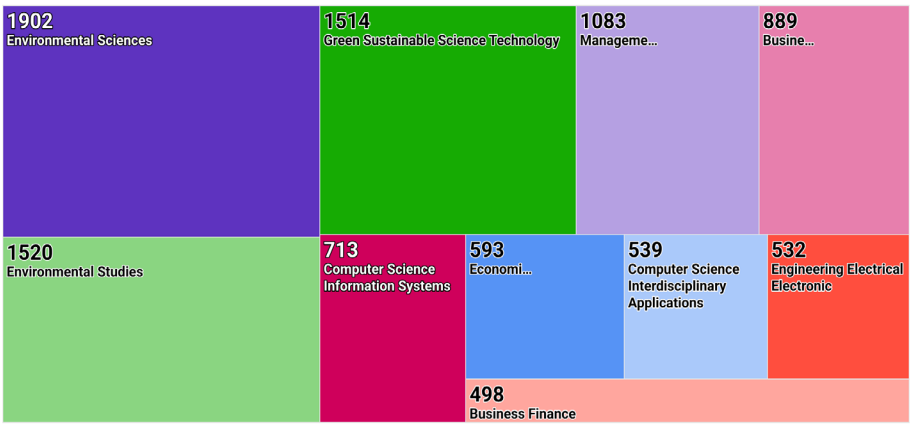

Figure 1. Interdisciplinary profile of the literature indexed in Web of Science Core Collection

Source: automatically generated by the Web of Science platform

However, the managerial relevance of the theme is validated by the critical mass of works indexed in the economic axis: Management (1083), Business (889), Economics (593) and Business Finance (498). This grouping indicates the effort of the scientific community to translate ecological indicators into corporate performance and rigorous control mechanisms. Moreover, convergence is ensured by the technological pillar, through Computer Science Information Systems (713), Interdisciplinary Applications (539) and Engineering Electrical Electronic (532), which provides the computational architecture necessary for the operationalization of intelligent systems. Consequently, these quantitative data fully justify the opportunity of this research. The integration of green digital twins into internal control systems is placed precisely at the unique intersection of these three major global paradigms: environmental urgency, advanced digital transformation, and responsible corporate governance.

Figure 2. shows the citation and publication report generated by the Web of Science platform which highlights a remarkable evolution in global scientific interest, characterized by a transition from a phase of slow accumulation to sharp exponential growth. Before 2022, the topic of integrating intelligent systems and sustainable development had a modest number of citations and a low impact factor, considered an experimental niche. A critical turning point occurred in 2022, when the academic community exceeded the psychological threshold of 500 publications and 10,000 citations in a single year. This acceleration was directly driven by the international adoption of new European and global guidelines on ESG reporting and industrial digitalization. The period 2022–2025 confirms the complete consolidation of this field. The figures grew steadily and aggressively, reaching a historic high of over 3,000 published articles in 2025 and having a huge impact on the scientific community, reflected in the 40,000-citation threshold being exceeded. The current 2026 horizon confirms the irreversibility of this trend. Although 2026 is not yet over, and metadata indexing is not yet fully completed, partial data

already points to impressive momentum: over 2,500 new papers have been published in a short period of time, accumulating a massive citation count of over 30,000. This mathematical model demonstrates that the topic discussed in this article is a dominant and relevant area of research that is at the epicenter of scientific debate in modern management.

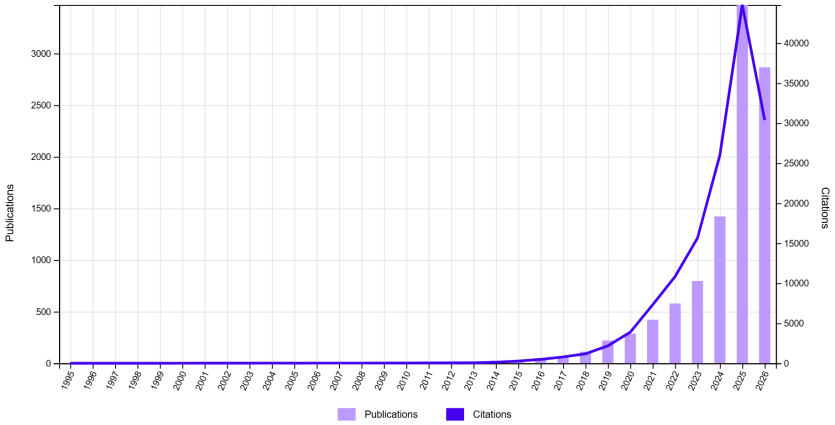

Figure 2. Annual evolution of scientific publications and citation counts indexed in Web of Science (1995 to 2026)

Source: automatically generated by the Web of Science platform

In Figure 3, we can visualize the network of keyword co-occurrence maps in VOSviewer, which reveals 5 clusters on green digital twins and internal management integration.

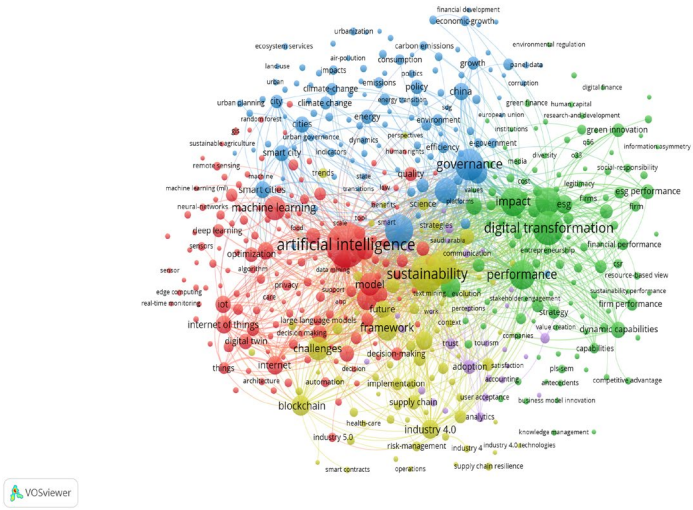

Figure 3. Bibliometric mapping of scientific literature on innovative managerial solutions and governance of intelligent systems

Source: Own elaboration based on Web of Science data processed via VOSviewer

A structural analysis of the red cluster, the largest in the network with 160 elements, clearly demonstrates that contemporary scientific literature revolves around an integrated technological-managerial core. The fact that boundary elements such as artificial intelligence, machine learning, the internet of things, and digital twins are located in the same cluster alongside the risk management component indicates a profound paradigm shift in corporate governance. This bibliometric configuration offers an innovative management solution, namely, internal control goes beyond its traditional retrospective function and becomes a proactive system. Analysis of this cluster demonstrates that "green" management using digital twins is not simply a technical problem, but a strategic solution in the field of internal control. By using machine learning on digital twin models, risk management becomes "smart," enabling continuous and automated monitoring of operational and environmental risks (Z. Zhang et al., 2025; Hao et al., 2022).

A structural analysis of the green cluster, comprising a significant number of 123 elements, shifts the focus from "how technology works" to "what value it creates" for the organization. Combining key terms such as digital transformation, technology, and information with innovation, performance, business, and the ESG component provides a clear understanding of the necessary innovative management decisions. The data in this cluster demonstrate that the integration of intelligent technologies into business structures not only facilitates operational optimization but also serves as a driver of sustainability-focused innovation. Thus, the impact of digital transformation is directly translated into a multidimensional ESG performance indicator. For managers, the 123 interconnected elements in this cluster confirm that responsible management of intelligent systems, such as digital twins, is a viable business strategy capable of balancing economic performance with the ethical and environmental values demanded by modern society (Nayal et al., 2021).

The analysis of the blue cluster, which comprises 116 elements, expands the research boundaries from the micro-organizational level to the macro-social context. The co-location of fundamental concepts such as governance, policy, and sustainable development, along with smart cities, digitalization, and big data, highlights a critical aspect of innovative management decisions. Data from this cluster demonstrate that the integration of "green" digital twins goes beyond simple production optimization, becoming a key component of smart urban and regional ecosystems. The 116 interconnected elements highlight the importance of aligning internal control systems with public policy and data governance frameworks. This cluster provides bibliometric evidence that the responsible use of big data within the framework of ethical and policy-oriented management is the only way for digitalization to ensure long-term economic growth while simultaneously protecting societal well-being (Abbas, 2025; Jing et al., 2025; Weil et al., 2023; Oláh et al., 2020).

The analysis of the yellow cluster, consisting of 73 elements, offers a deeply pragmatic perspective focused on implementation and operational architecture. The combination of the terms framework, implementation, and

challenges with disruptive technologies such as blockchain and structural pillars such as supply chain and the circular economy highlights an important dimension of the study. The data in this cluster demonstrate that the success of green digital twins critically depends on managers' ability to ensure security and optimize interorganizational logistics flows. Blockchain integration emerges as a dominant innovative management solution, providing the trust and traceability necessary for internal auditing and monitoring of green performance across the entire industry 4.0 value chain. This cluster emphasizes that the transition to a sustainable future requires a shift from theoretical models to rigorous implementation management strategies, providing clear tools for addressing the challenges of responsible technological integration.

The analysis of the purple cluster, although comprising a smaller number of 32 elements, highlights the most important pillar of the entire study, that of the human and behavioral aspect. Combining the concepts of adoption, trust, and user acceptance with information technology and accounting opens up a profound perspective on responsible management. The data in this cluster demonstrate that the success of innovative management decisions is determined by more than just the computing capabilities of intelligent systems. For a "green" digital twin to function as a legitimate internal control tool, management must cultivate employee and auditor trust in the correctness of the algorithms. This cluster confirms the fact that sustainable digital transformation is driven by the human factor. Reporting and control mechanisms must be designed to ensure transparency and social responsibility, transforming "cold" technologies into an integrated system that actively supports human values and professional ethics (Vinuesa et al., 2020; Pizzi et al., 2020).

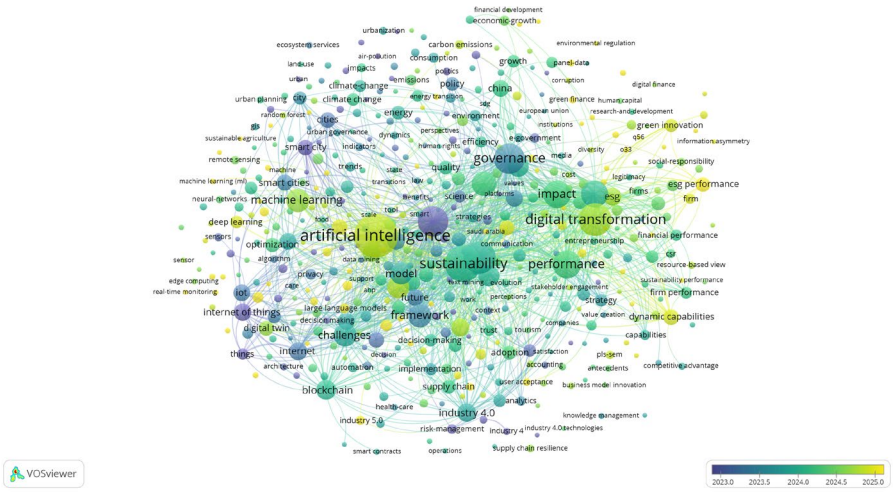

Figure 4. Temporal dynamics of the keyword co-occurrence network
Source: Own elaboration based on Web of Science data processed via VOSviewer

An analysis of the overlay visualization, illustrated in Figure 4, reveals a clear chronological trajectory in the specialized literature. In the period before 2023 and until the middle of it (2023.5), academic research focused primarily on establishing data infrastructure and defining observation frameworks (Lu et al., 2023; Calderon-Monge & Ribeiro-Soriano, 2023). The early, simultaneous emergence of key terms such as IoT, the internet of things, and big data reflects a phase in which the academic community was analyzing the technological potential of data collection, with the smart city ecosystem as its primary testing ground. From a management perspective, this period laid the foundations for modern internal control. The incorporation of governance and risk management concepts at this early stage demonstrates that the implementation of cyber-physical systems was organically accompanied by the need to reduce operational and security risks. Data for the period up to 2023.5 confirms that classic risk management systems formed the essential foundation without which the subsequent evolution toward modern predictive solutions would have been impossible.

The period from the second half of 2023 to early 2024 marks a critical stage of conceptual maturation, during which the academic focus shifts from a technocentric field to global responsibility. The co-emergence of the key terms sustainability, governance, and future, indicates a moment of organic integration of the green agenda into corporate governance strategies. From a methodological perspective, this period is defined by researchers' efforts to translate theory into applicable models, as evidenced by the centrality of the conceptual term and the realistic depiction of organizational barriers reflected in the concept of challenges. In this context, innovation plays a significant role, with blockchain technology emerging as one of the first innovative management solutions designed to ensure the security of non-financial reporting and robust support for internal audit. Data from 2023.5–2024 demonstrate that the literature has acted as a bridge, transforming the preexisting data infrastructure into a management system strategically oriented toward the sustainable economy of the future (Calderon-Monge & Ribeiro-Soriano, 2023).

The period from early to mid-2024 represents a period of empirical and institutional consolidation in the specialized literature. The combined use of the key terms impact and performance indicates a clear shift in academic interest from theoretical research to rigorous evaluation of the results achieved through digital transformation. From a management perspective, this stage marks the maturation of the control pillar. The integration of the concept of corporate governance alongside sustainability and quality demonstrates that oversight of intelligent systems has risen to the highest level of organizational decision-making. Thus, internal control is no longer simply a matter of procedural compliance but is becoming a strategic tool through which, corporate governance ensures the quality of non-financial data and the long-term viability of a sustainable business model. Data for the period 2024–2024.5 confirms that the effectiveness of cyber-physical technologies has begun to depend directly on the existence of strong and responsible governance

structures, paving the way for advanced automation in the coming years (Q. Zhang et al., 2025).

The chronological transition to the period 2024.5–2025 highlights a significant qualitative leap in the scientific literature, marked by the organic fusion of advanced analytical technologies and the fundamentals of applied sustainability. The terms digital transformation and machine learning occupy a central position, along with the concepts of circular economy and ESG. This demonstrates the shift from passive risk monitoring to predictive and automated optimization of environmental processes. This stage lays the scientific foundation for the intelligent use of "green" digital twins as advanced internal control mechanisms. Machine learning algorithms are no longer viewed as simple technical tools, but as innovative management solutions capable of managing resource flows, minimizing waste, and ensuring compliance with ESG standards. Furthermore, the literature has confirmed the ability of predictive algorithms to transform strategic environmental goals into measurable operational results, preparing the business ecosystem for the current phase of autonomy and social trust (D. Li et al., 2025; Latkovska et al., 2025).

The most recent period in the timeframe, spanning the period after 2025 and extending to 2026, marks a complete maturity phase in this field of research. The concurrent emergence of cutting-edge keywords such as artificial intelligence, deep learning, and digital twins, alongside robust strategic concepts such as dynamic capabilities, green innovation, and ESG performance, demonstrates the current state of innovative governance solutions. From a theoretical and practical perspective, the data from this recent period demonstrates that responsible digital governance has moved beyond simple operational tools. The integration of advanced artificial intelligence into internal control architecture serves as a genuine dynamic capability, providing organizations with the agility needed to quickly adapt to environmental challenges (Miró-Pérez et al., 2026).

Density visualization, shown in Figure 5, provides a clear structural perspective on the degree of consolidation in the research field. Areas of maximum brightness and density in the heat map identify consistent epistemological pillars around which the scientific literature gravitates: artificial intelligence, sustainability, management, governance, digital transformation, model, innovation, and big data (X. Li et al., 2023; M. Li, 2022; Kshetri, 2017). From a methodological perspective, this high-density configuration demonstrates that the topic of integrating intelligent systems into internal control is not isolated, but rather represents a convergence point for the most documented paradigms in modern management. The centrality of governance and management concepts, alongside artificial intelligence, and sustainability, confirms that contemporary research recognizes the need to shift from purely operational digitalization to responsible digital governance (Mithas et al., 2022; Nishant et al., 2020). Density analysis confirms the viability and scientific validity of this work, demonstrating that the use of digital twins as innovative management solutions directly

corresponds to the current direction of the specialized literature indexed in the Web of Science.

Although the network's core is firmly centered on traditional management concepts, an analysis of low-connection areas reveals the limits of this field's development. Terms such as green technology innovation, green finance, digital finance, human capital, supply chain resilience, and competitive advantages occupy peripheral positions and have low link counts in the current literature indexed in the Web of Science (Nativi et al., 2021; De Sousa Jabbour et al., 2018).

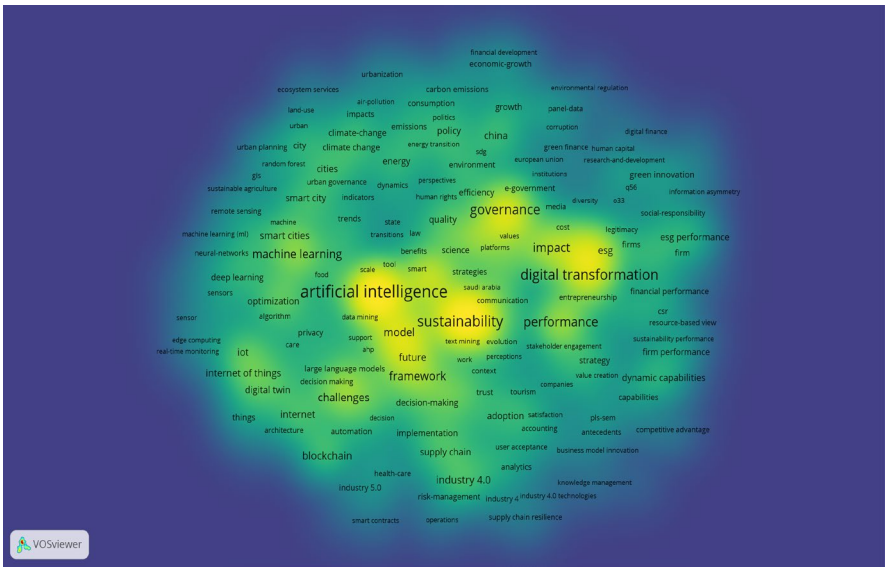

Figure 5. Density-based visualization of the bibliometric network revealing core concepts and peripheral niches

Source: Own elaboration based on Web of Science data processed via VOSviewer

This low density does not reflect a lack of relevance but rather points to critical gaps in current research. The literature has described in detail what a digital twin is, but too little has analyzed how it can be integrated with digital finance to support green finance projects or how it can develop human capital for supply chain resilience. Therefore, for future research, it is proposed to develop innovative management solutions to integrate green digital twins into internal control systems and transform these disparate niches into a single strategic capability able of generating sustainable competitive advantages and organizational resilience in the current environment.

3. Conclusions

This study presents a comprehensive and systematic mapping of the global scientific literature indexed in the Web of Science Core Collection, analyzing the structural, temporal, and density dynamics of the paradigms shaping the integration

of intelligent systems into sustainable management. A quantitative assessment confirms an exponential growth in academic interest, marked by a critical inflection point in 2022 and culminating in historical publication and citation rates in 2025–2026. This mathematical trajectory clearly demonstrates that the alignment of digital transformation with the climate agenda is not a short-term trend, but an irreversible paradigm shift in management sciences.

Structurally, the study reveals a deeply interdisciplinary profile, structured around three core pillars: environmental, technological, and corporate governance. The timeline reflects the conceptual evolution of this field, marking a shift from a purely technocentric approach based on raw data collection (aided by IoT and big data in the pre-2023 phase) to the conceptualization of rigorous compliance and audit frameworks (aided by blockchain in 2024), and then to the optimization of circular economy and ESG processes through machine learning (2025). The current 2026 horizon places research in a phase of full cognitive autonomy, where the convergence of artificial intelligence, deep learning, and digital twins transforms internal control architecture from a passive verification mechanism into a truly dynamic capability.

The contribution of this work lies in its integrative approach to emerging niches identified in areas with low bibliometric network density. While mainstream research typically analyzes cyber-physical technologies in isolation or strictly at the operational level, the model developed in this paper demonstrates how the integration of green digital twins into internal control systems can act as a strategic bridge. By linking green financing flows and ESG compliance with human capital development and supply chain resilience, the management solution provides organizations with a flexible governance framework capable of transforming environmental risks into sustainable competitive advantages.

While this study provides theoretical and empirical support for the strategic value of green digital twins, future research should focus on empirically validating the model through long-term case studies in industries with a high carbon footprint. Special attention should also be paid to the cultural and behavioral barriers associated with the adoption of AI-based technologies by human capital in audit and internal control systems.

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