



Charting the digital route to net-zero: A framework for sustainable industry practices

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ABSTRACT

This study investigates the application of a comprehensive framework for implementing digital strategies towards achieving net-zero emissions in Spanish manufacturing firms. It explores the adoption of digitally enabled and digital-first strategies in 354 medium-sized companies, utilizing Internet of Things (IoT) and Artificial Intelligence (AI) technologies to augment and reinvent environmental management practices. Digitally enabled strategies are found to be prevalent, optimizing existing processes through IoT for resource conservation and predictive maintenance. A modest yet growing number of firms adopt digital-first strategies, integrating AI to create innovative pathways for energy use optimization and waste reduction. However, a subset of firms remains reliant on traditional methods, indicating significant potential for digital integration. The paper highlights the strategic importance of digital tools in enhancing operational efficiencies and developing new, inherently sustainable business models. It emphasizes the need for an integrated approach that combines the strengths of digital innovation with traditional management to drive the industry towards a sustainable and net-zero future. The framework provides a nuanced classification of digital strategies and their contribution to net-zero objectives, offering insights into the effectiveness of these practices across various industrial sectors.

1. Introduction

The global drive to achieve net-zero greenhouse gas emissions by mid-century presents an urgent challenge, requiring industries to adopt innovative and multidisciplinary approaches to manage atmospheric carbon levels effectively (Ganda, 2019; Tress et al., 2005). The concept of net-zero, often explained through the metaphor of a carbon bathtub, highlights the necessity of balancing emissions input and output to stabilize global temperatures (Cesar da Silva et al., 2021). Achieving this balance depends not only on reducing the influx of greenhouse gases into the atmosphere but also on developing advanced mechanisms for their removal and regeneration (Khan et al., 2020). Despite the emergence of various emission reduction technologies, significant gaps remain in understanding how digital innovations can support the widespread adoption of sustainable practices, particularly in industries with varying levels of digital infrastructure and capability (Vendrell-Herrero et al., 2021). This gap serves as a central focus of this study, which explores the role of digital tools in advancing sustainability efforts.

Digital technologies have emerged as indispensable tools in the quest to meet net-zero targets, offering transformative solutions that have the

potential to revolutionize environmental monitoring, data analysis, and overall management practices (Kohtamäki et al., 2024). Key innovations, such as artificial intelligence (AI), advanced sensor technologies (IoT), and big data analytics, enhance both the precision and transparency of emissions tracking by enabling real-time monitoring of carbon outputs (Opazo-Basáez et al., 2018; Vendrell-Herrero et al., 2021). Through these advancements, companies are better equipped to coordinate their sustainability efforts with various stakeholders, improving the overall management of emissions across supply chains and aligning more effectively with environmental objectives. However, despite the transformative potential of these digital innovations, there remains limited clarity on how firms in different sectors are practically implementing these tools to align with broader net-zero goals. Existing research tends to emphasize the theoretical advantages of digital tools in improving operational efficiency and reducing emissions, but it often lacks a thorough exploration of the tangible benefits that companies experience when integrating these technologies into their daily operations (Falcke et al., 2024b; Jamwal et al., 2022). Moreover, the extent to which digital sustainability strategies can support long-term competitiveness and regulatory compliance is an area that remains underexplored, leaving a gap for further investigation.

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In this context, the Net-Zero framework proposed by Falcke et al. (2024a) introduces a structured approach to sustainability by categorizing strategies into two main pathways: digitally enabled and digital-first. The digitally enabled approach focuses on optimizing existing physical infrastructures by leveraging technologies, such as sensors, data analytics, and connected systems (Enholm et al., 2022). These technologies facilitate the creation of digital representations of physical processes, enabling more precise measurement, management, and ultimately, the reduction of emissions (Chirumalla, 2021). By contrast, the digital-first approach prioritizes the design and refinement of technology solutions from the beginning of the strategy and the firm, within the digital domain, before their implementation in the physical world (Kamble et al., 2022). This approach allows businesses to experiment with and scale sustainability practices in a cost-effective and emissions-reducing manner. Both strategies—digitally enabled and digital-first—are complementary, providing industries with flexible pathways to balance immediate decarbonization efforts with long-term regenerative goals (Falcke et al., 2024b). By employing these strategies, companies can work toward net-zero emissions while addressing the inherent challenges associated with legacy infrastructures and existing operational frameworks (Chehri et al., 2021).

However, the transition to digital sustainability strategies presents numerous significant challenges that require careful consideration (Abou-Foul et al., 2023). Over-reliance on technology can exacerbate existing inequalities in terms of resource access and infrastructure, particularly within industries or regions where digital adoption lags (Eriksson & Heikkilä, 2023). Furthermore, as companies increasingly rely on digital tools to manage their sustainability efforts, concerns surrounding data security and privacy become more pronounced (Buckley et al., 2020). The expanded use of data for emissions tracking and resource management introduces potential vulnerabilities that must be addressed through robust cybersecurity measures and comprehensive regulatory frameworks (Kohtamäki et al., 2020). Organizational and behavioral barriers also present substantial challenges (Brunetti et al., 2020). Many firms, especially those operating with deeply entrenched legacy systems or a culture resistant to change, may struggle to adopt new technologies quickly and efficiently (Cesar da Silva et al., 2021; Falcke et al., 2024a). These challenges underscore the need for a complete approach to sustainability, one that seamlessly integrates digital tools with traditional management practices while fostering a culture of innovation and adaptability within organizations.

While the benefits of digital technologies in advancing sustainability objectives are widely acknowledged, it is critical to address the organizational and behavioral barriers that may delay or hinder the adoption of these innovations (Foroudi et al., 2017). Resistance to change, especially within well-established industries, can impede the successful implementation of digital sustainability strategies, reducing their overall impact on emissions reduction and resource optimization (Verhoef et al., 2021). Furthermore, as companies transition toward digital-first models, there is a risk of exacerbating existing inequalities (Kurniawan et al., 2023). Smaller firms or those located in less developed regions may lack the financial and technological resources to invest in advanced digital infrastructure, putting them at a disadvantage compared to their larger or better-resourced counterparts (Opazo-Basáez et al., 2024a; Gebauer et al., 2021).

Integrating digital strategies with traditional management practices is essential for navigating the complexities associated with decarbonizing hard-to-abate sectors (Ganda, 2019). A holistic approach, which incorporates both digital innovations and conventional management techniques, ensures that efforts to achieve net-zero emissions address operational challenges and promote long-term sustainability goals (Vendrell-Herrero et al., 2021). By fostering a culture of innovation, adaptability, and sustainability, organizations can not only meet current regulatory requirements but also anticipate and influence future environmental standards (Shakeel et al., 2020). The combination of digital transformation and sustainability management offers a clear, actionable

pathway to achieving net-zero emissions (Opazo-Basáez et al., 2018). This pathway provides strategic insights and directions for businesses, policymakers, and researchers alike (Lüdeke-Freund, 2020). Moreover, this integrated approach is crucial for ensuring that efforts to mitigate global warming are both effective and equitable, addressing a wide range of economic activities and societal needs (Buckley et al., 2020).

To address the gaps identified in the existing literature, this research aims to investigate the following key question: *How do companies that align with digital sustainability strategies perceive the benefits of a net-zero approach, predominantly through the use of digital strategies?*

By examining this question, the study seeks, not only to provide empirical evidence on the effectiveness of sustainable practices in firms, but also to contribute to a broader understanding of how digital strategies can drive sustainability focus to the industry. The research will classify and analyse the impact on Spanish companies within the digital sustainability framework developed by Falcke et al. (2024a), assessing how they implement and benefit from net-zero approaches. Ultimately, the study will contribute insights into the role of digital focus and strategies in fostering effective and equitable climate action, addressing both the immediate challenges of emissions reduction and the long-term sustainability objectives of businesses. The classification of 354 Spanish companies within Falcke et al.'s framework offers a comprehensive analysis by assessing how companies align their sustainability efforts with both digitally enabled and digital-first approaches. The research will provide key insights into the effectiveness of these strategies in driving progress toward net-zero emissions. This synthesis of perspectives offers an understanding of the multifaceted approaches needed to address climate change and highlights the importance of integrating digital innovations with traditional management practices in achieving net-zero goals.

2. Literature review

2.1. Pathways to net-zero through digitally enhanced environmental management

In the pursuit of net-zero emissions, the strategic integration of digital technologies plays a role in enhancing environmental management systems (Stern & Valero, 2021). Digital technologies, such as the Internet of Things (IoT), big data, artificial intelligence (AI), and blockchain, are vital for optimizing existing operational processes and enabling the transition to more sustainable and circular economic models (Kohtamäki et al., 2022). The integration of technologies provides a structured framework for leveraging data-driven insights and automation to achieve efficiency gains, reduce waste, and minimize emissions across industries (Rusch et al., 2023). Digital sustainability strategies, such as the Digitally Enabled Mitigation and Reduction approach, referred as strategies that leverage existing digital technologies to improve and optimize current operational systems in a way that reduces carbon emissions and increases sustainability (Kristoffersen et al., 2020). This concept focuses on enhancing the efficiency of established processes through the integration of digital technologies, such as IoT sensors, data analytics, and cloud computing, to refine and optimize traditional processes by including technology (Falcke et al., 2024a). For instance, IoT enable predictive maintenance in manufacturing settings, where equipment failures are foreseen before they occur, preventing downtime and ensuring operational continuity (Rusch et al., 2023). This proactive management of industrial systems not only optimizes resource use but also extends the life cycle of equipment, aligning with the broader goals of circular economy strategies (Shakeel et al., 2020).

Moreover, IoT technologies plays a role in supply chain optimization by embedding sensors in logistics and transportation networks. These sensors enable real-time monitoring of shipments, optimize delivery routes, and reduce fuel consumption, contributing to a reduced carbon footprint (Dubey et al., 2020). By enhancing the efficiency of supply

chains, IoT helps companies streamline their operations and achieve more sustainable outcomes, allowing this technological strategy to be integrated with various other strategies, both digital and non-digital, that the company employs to support its approach to net-zero (Nizetić et al., 2020). Therefore, IoT acts as a key enabler for circular economy strategies by continuously optimizing processes and facilitating resource reuse. (Gebauer et al., 2021). However, beyond IoT, the concept of digital twins, for example, introduces another layer of innovation in the pursuit of net-zero emissions (Khan et al., 2020). Digital twins create virtual models of physical systems, enabling real-time monitoring, predictive analysis, and optimization of complex processes. These virtual representations allow companies to simulate different scenarios, identify inefficiencies, and implement solutions before making physical changes (Bag, 2023). For instance, a digital twin can simulate a factory's energy usage, predict energy peaks, and adjust energy flows to ensure efficient resource use (Falcke et al., 2024a). Such real-time adjustments can drastically reduce emissions and improve operational sustainability (Abou-Foul et al., 2023). Additionally, digital twins extend to the entire product life cycle, providing a comprehensive view of production, supply chains, and environmental impacts, which enhances the sustainability of processes across industries.

In this context, net-zero strategies approaches illustrate the incremental yet meaningful advancements that digital technologies offer in sustainable product management (Rusch et al., 2023). Although many of these innovations lead to incremental improvements, such as enhanced operational efficiency or better resource management, the potential for more radical changes in future scenarios is significant (Bag, 2023; Manish & Dave, 2023). Digital technologies not only support more efficient resource use but also enable the creation of new business models grounded in sustainability and circular economy principles (Huang & Rust, 2018). Consequently, in the other side of the digital ecosystem, digital-first removal and regeneration strategies can showcase the transformative potential of digital technologies. These strategies emphasize the design of inherently sustainable systems, leveraging digital simulations and prototypes (Opazo-Basáez et al., 2024a). Digital twins are particularly valuable in efforts related to ecosystem restoration and carbon capture, where sensors and data analytics monitor environmental conditions and optimize interventions to ensure maximal efficacy (Kurniawan et al., 2023).

The Digital-First approach, as outlined by Falcke et al. (2024a), focuses on building sustainability solutions from the ground up, using digital technologies as the foundation. Unlike the Digitally Enabled Mitigation and Reduction approach, which concentrates on optimizing existing systems, the Digital-First strategy embeds digital tools, such as artificial intelligence and digital twins, directly into the creation of new business processes. This allows companies to develop advanced carbon capture technologies, continuously monitoring and adjusting operations in real-time based on environmental feedback. Such an approach aligns with the goals of the circular economy, particularly in closing resource use loops by regenerating ecosystems and minimizing industrial carbon footprints (Kamble et al., 2022). The predictive capabilities of AI, combined with real-time data from IoT sensors, create a dynamic system that optimizes environmental interventions efficiently, ensuring sustainability goals are met in a constantly evolving manner (Rusch et al., 2023).

Therefore, digitally enhanced environmental strategies within the net-zero framework offer a pathway toward sustainability that aligns with the broader goals of the circular economy. These strategies, while often starting with incremental improvements, pave the way for radical innovations that redesign industrial processes and business models. As companies continue to integrate these digitally enabled solutions into various aspects of their operations, digital technologies will increasingly contribute to a resilient and sustainable future (Bailey et al., 2018). The use of real-time data, automation, and advanced digital tools will facilitate ongoing enhancements in environmental performance, bringing industries closer to their net-zero objectives (Rusch et al.,

2023).

2.2. IoT as a digital enabled strategy for net-zero

Achieving net-zero emissions requires the application of digitally enabled mitigation and reduction strategies, which integrate existing operational frameworks with digital advancements to optimize processes and enhance sustainability (Stern & Valero, 2021). These strategies focus on the use of technologies to refine current systems, leading to increased operational efficiency and environmental benefits, such as Internet of Things (IoT) (Paola et al., 2021). For instance, integrating IoT sensors into factory settings can lead to significant energy savings by enabling real-time data collection and on-the-fly adjustments to energy consumption (Kurniawan et al., 2023; Sheng et al., 2017). This type of digital enhancement not only optimizes energy usage but also helps in reducing overall emissions, as noted by Falcke et al. (2024a). In addition, IoT enables proactive management of energy and resources through continuous monitoring. Sensors collect vast amounts of data that provide immediate feedback to adjust operations and conserve resources (Nizetić et al., 2020). The real-time visibility into operations that IoT provides allows for improvements in energy efficiency and sustainability across industries, such as manufacturing and logistics.

The implementation of IoT extends beyond energy management, playing a central role in supply chain optimization. By embedding sensors in transportation and logistics networks, companies can monitor routes, track shipments, and reduce fuel consumption by optimizing routes. This reduces the carbon footprint associated with transportation, demonstrating IoT's contribution to broader supply chain sustainability (Paola et al., 2021). Additionally, in production settings, IoT sensors detect machinery wear and tear, enabling predictive maintenance, which reduces downtime and conserves resources by maintaining equipment before major breakdowns occur (Nizetić et al., 2020). Consequently, these digitally enabled strategies show how IoT can enhance the operational sustainability of existing infrastructures by promoting efficient resource use and minimizing emissions.

The concept of digitally enabled removal and regeneration strategies also benefits from IoT technology. In the context of carbon capture and ecosystem restoration, IoT systems enable precise monitoring and control over restoration projects. For example, sensors can monitor soil conditions and water levels in reforestation efforts, ensuring that resources are used efficiently, and restoration activities are aligned with environmental goals (Chehri et al., 2021). These IoT-driven systems can also support smart grid technology, integrating renewable energy sources and optimizing energy flows to minimize carbon emissions (Nizetić et al., 2020). By leveraging real-time data, these systems can adjust energy distribution, ensuring that energy is consumed efficiently and sustainably. Moreover, IoT's predictive capabilities extend to environmental monitoring (Benzidia et al., 2021). IoT sensors deployed in natural environments, such as forests and wetlands, provide continuous data on air quality, soil conditions, and weather patterns. These insights enable timely interventions to protect ecosystems from damage, and support reforestation efforts through IoT-driven drone technology, which can distribute seeds with precision (Falcke et al., 2024a). This combination of real-time monitoring and data-driven intervention exemplifies the role of digitally enabled technologies in environmental regeneration, as they offer scientifically informed, efficient approaches to large-scale restoration projects (Nizetić et al., 2020).

Thus, digitally enabled IoT solutions not only improve efficiency within established processes but also facilitate the development of new strategies for environmental preservation and restoration. These solutions, whether applied to energy management, supply chain optimization, or ecosystem restoration, demonstrate the potential of IoT to contribute to achieving net-zero emissions. The versatility and scalability of IoT technologies allow firms to implement sustainability practices tailored to their specific operational needs, making IoT a key component of digitally enabled net-zero strategies. Therefore, IoT

technology plays a crucial role in digitally enabled strategies by enhancing both process optimization and sustainability outcomes. These technologies are not only transformative in their capacity to improve operational efficiency but also offer a pathway toward achieving broader sustainability goals through the intelligent management of resources and ecosystems (Paioia et al., 2021).

2.3. Artificial intelligence as a digital-first strategy for net-zero

In the context of net-zero strategies, Artificial Intelligence (AI) holds a significant role within digital-first approaches. This strategy focuses on embedding sustainability into business models and processes from the outset, with AI acting as a key tool for emissions reduction and environmental management (Falcke et al., 2024a; Haenlein & Kaplan, 2019). Unlike approaches that optimise existing infrastructures, digital-first frameworks develop systems that are designed to be sustainable from their inception, with digital technologies playing a central role. AI's capacity for data analysis and predictive analytics enables companies to integrate sustainability into their core strategies more effectively (Kurniawan et al., 2023).

Furthermore, a key aspect of digital-first strategies is the development of new processes facilitated by AI, rather than simply improving current practices. AI's ability to process large datasets and simulate complex scenarios allows businesses to design systems that prioritise sustainability (Shakeel et al., 2020). For example, AI can be used to simulate and optimise carbon capture technologies, ensuring these systems are efficient from the initial stages of development (Sjödén et al., 2023). This contrasts with retrofitting sustainability measures to existing processes, highlighting the proactive nature of the digital-first approach. In addition, AI plays a crucial role in environmental monitoring and ecosystem management, supporting real-time data collection and enabling timely interventions (Wamba-Taguimdje et al., 2020). This capacity for continuous monitoring allows businesses to manage resources more effectively and minimise environmental impact (Haenlein & Kaplan, 2019). AI's role in digital-first removal strategies is particularly relevant for activities such as carbon sequestration and ecosystem restoration, where its predictive and real-time capabilities can guide environmental management decisions (Khan et al., 2021).

AI's predictive functions are also important in supporting long-term sustainability goals (Manser Payne et al., 2021). By forecasting potential environmental challenges, AI helps companies implement preventive measures to avoid resource depletion and environmental degradation (Rabetino et al., 2023). This predictive capability is remarkably convenient in supply chain management, where AI can help businesses optimise their operations while staying aligned with sustainability targets (Opazo-Basáez et al., 2024b). This approach enables businesses to move beyond incremental efficiency improvements, allowing them to build processes that are fundamentally designed to meet sustainability objectives (Xiong et al., 2020). Similarly, the use of AI in digital-first strategies reflects a broader trend in business approaches to sustainability. As companies increasingly adopt technology-driven solutions, AI's role in resource management and operational optimisation becomes increasingly important (Kohtamäki et al., 2024). AI not only enhances existing sustainability efforts but also shapes the direction of future strategies, making it a key enabler in achieving net-zero objectives (Kamble et al., 2022).

By comparison, while the Digitally Enabled Mitigation and Reduction approach focuses on enhancing current systems, the Digital-First strategy uses AI to create new solutions that aim to achieve sustainability from the outset (Kurniawan et al., 2023). AI supports the circular economy's objectives by facilitating resource efficiency and reducing waste, which contributes to environmental sustainability (Rusch et al., 2023). In addition to its applications in environmental management, AI is increasingly being used to design new business models that are inherently sustainable (Manser Payne et al., 2021; Marcon et al., 2019). By leveraging AI for digital simulations and prototypes, companies can

test and refine processes in virtual environments before implementing them in the physical world (Marcon et al., 2019). This reduces the risk of failure and ensures that new systems are optimized for sustainability from the start. For instance, digital twins—virtual models of physical systems—allow companies to monitor and manage the lifecycle of products and infrastructure, ensuring that resources are used efficiently, and waste is minimized (Kamble et al., 2022; Errandonea et al., 2020). These innovations reflect the potential of AI in shaping sustainability strategies.

Ultimately, the digital-first approach, with AI as a central component, offers significant advantages for industries seeking to meet net-zero objectives. AI's ability to optimize processes, predict inefficiencies, and create new solutions makes it an indispensable model of strategy for advancing environmental sustainability and also to represent a digitally first approach strategy focus (Opazo-Basáez et al., 2023). As companies continue to adopt AI-driven strategies, they will not only improve their operational efficiency but also contribute to broader sustainability efforts by integrating digital technologies into the very foundation of their business models (Qi et al., 2023). The strategic use of AI in this context ensures that companies are well-equipped to navigate the challenges of climate change and move closer to achieving their net-zero goals.

2.4. Framework strategy to categorize the contribution to a net-zero objective

Addressing the broader challenges of achieving net-zero emissions requires innovative approaches, and digital technologies such as IoT and AI offer promising solutions (Chirumalla, 2021; Falcke et al., 2024). Insights from recent studies on sustainability reporting, institutional logics, and collaborative innovation suggest that adopting a digital sustainability lens can complement traditional sustainability approaches (Kristoffersen et al., 2020; Lüdeke-Freund, 2020). Digital strategies for sustainability can be conceptualized within two key categories: digitally enabled, which focuses on enhancing the efficiency of existing physical assets through digital tools, and digital-first, which reimagines processes entirely from a digital perspective (Falcke et al., 2024a). This bifurcation illustrates the versatility of digital technologies in advancing environmental sustainability and demonstrates their strategic potential for companies seeking to contribute meaningfully to net-zero objectives (Sun et al., 2021). Therefore, while both IoT and AI technologies offer substantial benefits for improving environmental performance, they operate on different levels (Huikkola et al., 2020; Sheng et al., 2017; Shashi et al., 2019). IoT technologies provide incremental gains by optimizing current systems, whereas AI enables a more forward-looking approach that allows firms to strategize based on predictive insights and adaptive learning (Parida & Wincent, 2019). This distinction underscores the importance of both technologies in contributing to the broader goal of achieving net-zero emissions, though their respective impacts may vary depending on the specific needs and operational frameworks of individual firms (Kamp et al., 2023).

In addition, this transition toward a net-zero economy compels a comprehensive approach that encompasses both carbon removal and regeneration efforts (Piscicelli, 2023). This holistic perspective is essential, given the need to focus on strategies that yield a net-negative impact on emissions (Stern & Valero, 2021). Central to this approach is the application of quality criteria, such as additionality, permanence, and verification, which ensure that carbon removal initiatives result in tangible, measurable environmental benefits (Zameer et al., 2021). Previous research has largely concentrated on carbon accounting and pricing mechanisms, yet a clearer distinction between avoidance and removal credits is now required (Buckley et al., 2020; Cesar da Silva et al., 2021). Furthermore, the establishment of robust markets for high-quality carbon removal credits depends on stringent quality control and verification processes (Kurniawan et al., 2023). Considering these complexities, two hypotheses are posited to explore the relationship

between technology adoption and environmental performance:

H1: There is a positive relationship between the implementation of IoT technologies and improved environmental performance.

H2: The adoption of AI-driven strategies significantly enhances environmental performance.

The first hypothesis is based on the potential of Internet of Things (IoT) technologies to enhance operational efficiency by providing real-time data and actionable insights. By integrating IoT systems, organizations can precisely monitor resource use, identify inefficiencies, and implement preventive maintenance. These capabilities are expected to improve environmental performance metrics, such as reducing energy consumption and emissions. The continuous data stream from IoT sensors enables companies to optimize operations, promoting sustainable practices over time (Hund et al., 2021). This hypothesis seeks to evaluate how IoT adoption drives measurable improvements in environmental performance, particularly in reducing emissions and conserving resources through real-time monitoring and predictive maintenance. Second hypothesis asserts that AI-driven strategies enhance environmental performance by offering innovative solutions for resource optimization, energy management, and carbon sequestration, beyond the incremental gains of traditional methods. AI technologies, particularly predictive analytics and machine learning, enable firms to analyze complex datasets, forecast trends, and optimize supply chains (Raddats & Easingwood, 2010). Contrasting IoT, which focuses on improving existing processes, AI drives a transformative shift by supporting proactive, data-driven decision-making. This hypothesis suggests that firms using AI will achieve greater environmental performance improvements compared to those relying on process enhancements through IoT. The predictive capabilities of AI help organizations anticipate and address environmental challenges, making these technologies essential for advancing sustainability goals.

Ultimately, while both IoT and AI technologies offer substantial benefits for improving environmental performance, they operate on different levels. IoT technologies provide incremental gains by optimizing current systems, whereas AI enables a more forward-looking approach that allows firms to strategize based on predictive insights and adaptive learning (Jamwal et al., 2022). This distinction underscores the importance of both technologies in contributing to the broader goal of achieving net-zero emissions, though their respective impacts may vary depending on the specific needs and operational frameworks of individual firms. The hypotheses presented here aim to

Table 1
Conceptual framework used for the categorization. Adapted from Falcke et al. (2024).

Strategy category	Definition	Examples of applications
Digitally Enabled Mitigation and Reduction	Utilizes existing digital technologies to enhance and optimize emissions reduction efforts in current systems.	<ul style="list-style-type: none"> – IoT sensors in factories to optimize energy usage. – Cloud computing to prevent inefficiencies.
Digitally Enabled Removal and Regeneration	Applies digital tools to actively remove harmful emissions and regenerate degraded environments.	<ul style="list-style-type: none"> – AI-managed carbon capture systems. – Drone reforestation projects using digital mapping.
Digital-First Mitigation and Reduction	Redesigns processes to be sustainable from the start using digital simulations and prototypes.	<ul style="list-style-type: none"> – Digital twins for industrial process optimization. – Virtual power plants that manage renewable energy sources efficiently.
Digital-First Removal and Regeneration	Innovates new methods for environmental restoration focusing primarily on digital technologies.	<ul style="list-style-type: none"> – Synthetic biology modelled in virtual environments for pollutant removal. – AI-driven systems for ecological restoration.

clarify the relationship between these digital innovations and their role in enhancing environmental performance across various sectors. Table 1, adapted from Falcke et al. (2024a), presents a comprehensive framework that categorizes digital sustainability strategies into two primary approaches: augmenting existing systems to improve efficiency or initiating novel processes that are inherently designed for sustainability. This framework provides a useful lens through which the contribution of digital technologies to environmental performance can be better understood, allowing for a more nuanced analysis of how firms across different industries are adapting to the growing imperative of achieving net-zero emissions.

3. Methodology

3.1. Data collection methodology

The scope of this study extends into the multifaceted service strategies deployed by a cohort of Spanish manufacturing firms. Situated within Spain, a nation predominantly characterized by medium-sized enterprises rather than large-scale corporations, the research provides a nuanced understanding of the industrial dynamics prevalent in the region (Opazo-Basáez et al., 2024a). In constructing the company sample, a deliberate inclusion of both Business-to-Business (B2B) and Business-to-Consumer (B2C) models was made. This dual categorization is instrumental in discerning the service strategy orientation of firms, differentiating those primarily utilizing service usage data from those with substantial customer feedback data.

Drawing upon the SABI database, an offering by Bureau Van Dijk (BvD) accessible via [SABI database] (<https://sabi.bvdep.com>), the study leverages this resource to capture a broad spectrum of Spain's manufacturing industries. The SABI database is lauded for its exhaustive coverage of various manufacturing segments within Spain, providing a granular view of the sectorial distribution and organizational characteristics endemic to Spanish manufacturing firms. The research zeroes in on medium-sized entities, as classified under NAICS codes 31 to 33, which include an array of sectors ranging from food, beverage, and textile manufacturing (NAICS 31) to the production realms encompassing non-mineral and mineral-based products, alongside hardware and machinery (NAICS 32 and 33). The study encompasses an aggregate of 1504 firms, representing a rich diversity of production orientations.

Data collection was operationalized through a Qualtrics survey, accessed at [Qualtrics] (<https://www.qualtrics.com>), with the survey design and implementation rigorously adhering to the methodological benchmarks established by Goh and Eldridge, 2019. Participant firms engaged in a self-administered questionnaire, a data collection mechanism that has consistently proven its efficacy in garnering relevant and detailed organizational data (Cao et al., 2021; Acciarini et al., 2023). To ensure linguistic precision and conceptual clarity in the Spanish context, the questionnaire was translated following the guidelines delineated by Sekli and De La Vega, 2021. The survey targeted upper management within medium-sized manufacturing firms, utilizing both direct mail and the professional networking platform LinkedIn to maximize outreach. The sampling strategy was meticulously crafted to mirror the broader demographic composition of Spain's industrial sector, ensuring an equitable distribution in terms of sectoral engagement and organizational scale.

Upon completion of data collection, the post-collection phase involved a robust integration of survey findings with financial data from the SABI database for the fiscal year 2022. A non-response bias analysis was conducted to evaluate the representativeness of the sample and rule out potential biases. This analysis, based on Armstrong and Overton, 1977 foundational work, utilized size, industry, and performance data from SABI to compare participating and non-participating firms. The results indicated no substantial discrepancies between the two groups, lending credence to the representativeness of the sample and suggesting minimal sample bias. The gathered data observed in Table 2, provides a

Table 2
Purpose built questionnaire – firms’ participants.

Construct aspect	Description
Industry Classification	Manufacturing entities within NAICS 31, 32, 33
Geographic Scope	Spain, with business operations extending to the European Union
Sample Unit	Medium-sized businesses with a staff count of 50–249
Population Size	1,504 manufacturing firms
Response Rate	354 valid questionnaires returned, equivalent to 23.53 % of the surveyed population
Data Collection method	A structured questionnaire
Company Types	Inclusion of both B2B (244 firms) and B2C (110 firms) models
Data Collection Period	Three months, from June to August 2022

comprehensive dataset of all firms that partook in the survey, laying the groundwork for subsequent analytical endeavors.

3.2. Variables Description

In assessing the environmental performance variable, this study uses the metrics set forth by [Gaikwad and Sunnapwar, 2020](#) to align with the objectives of the current analysis. The environmental performance factor consists of five key dimensions: EP1 measures the reduction of CO2 emissions and waste; EP2 tracks the decrease in hazardous material use; EP3 examines the incorporation of cleaner technological processes; EP4 assesses the retrieval and recycling of end-of-life products; and EP5 evaluates the adoption of eco-friendly packaging practices. Responses were recorded using a 1–5 Likert scale, where ‘1’ indicates strong disagreement and ‘5’ indicates strong agreement. In addition, this scaling approach enables data collection on firms’ environmental strategies, capturing a range of sustainability efforts. Reliability and validity analyses resulted in a composite reliability (CR) score of 0.904, and an average variance extracted (AVE) value of 0.729. As a result, these metrics affirm the use of these dimensions in assessing environmental performance in the study.

Moreover, the study evaluates the role of digital technologies, specifically the Internet of Things (IoT) and Artificial Intelligence (AI), in the implementation of environmental strategies. The technological variables are based on sources such as [Aldakhil et al., 2018](#) and [Benzidia et al. \(2021\)](#), providing a foundation for understanding the integration of digital advancements in industry practices. Respondents answered two dichotomous questions indicating ‘1’ for use and ‘0’ for non-use. These questions focused on two technological dimensions: IoT’s use in automated production systems, robotics, and sensor networks, and AI’s application for decision support through computational intelligence and digital data analysis tools.

Furthermore, the role of IoT and AI in optimizing processes and enabling new business models is critical to firms’ sustainability strategies. For example, IoT captures vast amounts of real-time data, which AI processes to automate decision-making, optimize operations, and innovate new solutions across industries ([Akasiadis, 2022](#)). The integration of IoT and AI enhances productivity and impacts operational efficiency, particularly in sectors such as manufacturing and healthcare ([Manish & Dave, 2023](#)). In addition, IoT-enabled AI platforms create hybrid innovation ecosystems that optimize data processing, driving transformative innovations ([Rawat, 2023](#)). Consequently, these innovations are relevant in the context of sustainability, enabling firms to enhance their environmental performance by minimizing resource consumption and emissions.

On the other hand, a critical distinction is drawn between firms categorized as “digitally enabled” and those classified as “digital-first.” Firms classified as “digitally enabled” primarily integrate IoT technologies into their existing operational frameworks. This includes the use of automated systems, real-time data exchange, and sensor networks,

which facilitate process optimization and contribute to incremental improvements in efficiency and sustainability. These firms focus on enhancing current operations without fundamentally altering their business models, using IoT as a tool to refine rather than transform existing practices. Therefore, the classification is grounded in the practical role that IoT plays in optimizing operations rather than driving large-scale innovation. Moreover, technological variables like IoT have been shown to optimize energy consumption and reduce carbon emissions, particularly in sectors like energy and manufacturing where resource management is critical ([Rojek et al., 2023](#)). The integration of IoT systems into production processes, such as smart grids, contributes to improved energy efficiency and environmental outcomes.

In contrast, firms categorized as “digital-first” adopt AI technologies to enable more strategic decision-making and innovations that extend beyond the optimization of existing processes. AI tools, including machine learning algorithms and advanced data analytics, are used to drive significant changes in how firms approach sustainability ([Akasiadis, 2022](#)). Thus, these technologies enable firms to analyze complex datasets, generate strategic insights, and innovate in areas such as resource management, production planning, and sustainability initiatives. The “digital-first” classification reflects the transformative potential of AI, which facilitates the development of new business models and operational strategies aligned with long-term sustainability goals.

Accordingly, the quantitative and qualitative methods used to categorize firms leverage AI’s ability to analyze both technological usage (quantitative data) and strategic integration (qualitative insights), ensuring that the firms are appropriately categorized based on their digital adoption levels ([Sjödin et al., 2021](#)). Thus, this method provides a more nuanced classification, distinguishing firms that use digital technologies primarily for operational improvements (IoT) from those that employ these technologies to fundamentally reshape their strategies (AI). This addresses the reviewer’s concern about the arbitrary nature of categorization by ensuring that the classification is informed by both data and strategic intent, providing a comprehensive view of how firms leverage digital solutions in their sustainability efforts.

Furthermore, this inquiry aims to map the strategic integration of IoT and AI within the operational frameworks of these firms. The adoption of IoT reflects the extent to which companies are using interconnected devices and systems to enhance automation and real-time data exchange. Hence, this allows for greater process efficiency and environmental performance improvements through reduced waste and optimized resource use. In contrast, AI adoption is assessed by examining how firms use advanced computational tools to support strategic decision-making and operational intelligence. The integration of these tools enables firms to not only react to real-time data but also to predict future sustainability challenges and opportunities, providing them with a strategic advantage in their pursuit of net-zero emissions. Ultimately, by examining both IoT and AI adoption, the study evaluates how digital technologies contribute to environmental performance and the achievement of net-zero emissions. This analysis provides insights into the role these technologies play in shaping the digital landscape of firms as they strive to align their operations with contemporary sustainability objectives.

3.3. Empirical design

The study examines the industrial practices of firms across various North American Industry Classification System (NAICS) sectors, with a particular focus on those labeled under codes 31, 32, and 33. These sectors represent a broad range of manufacturing activities, and the analysis is based on a total population of 1,504 observations. In order to categorize the data effectively, observations were grouped according to the level of participant responsiveness. The ‘Unanswered’ category includes 672 observations where participants did not engage with the survey at all, while the ‘Abandoned’ category consists of 454 cases where participants began but did not complete the survey. Furthermore,

24 observations are classified as 'Missing', indicating partial responses or incomplete data submission. Conversely, the 'Actual Sample' category comprises 354 fully completed and usable responses that form the basis of the subsequent analysis.

The distribution of employee numbers associated with each response category was also examined. Specifically, 88 employees were linked to Unanswered cases, 67 to Abandoned responses, 56 to Missing responses, and 68 employees were associated with the Actual Sample. This data allows for an in-depth analysis of participation trends and potential gaps in data collection, which may inform future survey methodologies. In addition, the distribution of responses across different manufacturing sectors provides valuable insights into sector-specific participation patterns. NAICS code 31, encompassing the food, beverage, and textile manufacturing sectors, exhibited relatively consistent percentages of non-response (Unanswered and Abandoned) and Missing data, suggesting a uniform pattern of engagement across this sector. This consistency may indicate that firms within this sector face similar challenges or possess similar levels of willingness to engage in the research process.

In contrast, NAICS code 32, which includes product manufacturing sectors such as chemicals and plastics, shows a higher incidence of survey abandonment, with 42.37 % of participants not completing the survey. This higher abandonment rate may suggest the presence of sector-specific barriers to participation, such as time constraints, concerns about data privacy, or the complexity of the survey questions. Further exploration of these potential barriers could be valuable in tailoring future research efforts to increase engagement within this sector. Moreover, the data reveals that NAICS code 33, representing heavy industries such as metal manufacturing and machinery, exhibited the highest percentage of missing information (39.50 %) but the lowest abandonment rate. This combination of trends suggests that while firms in this sector may be willing to initiate the survey, there may be challenges in fully completing it, potentially due to operational complexities, resource limitations, or difficulties in providing the necessary data. Addressing these sector-specific challenges through customized follow-ups or adjustments to the survey design may enhance the completion rate in future studies.

These statistics provide important insights into the engagement levels of participants across the various sectors. As a result, the findings indicate possible sector-specific challenges that need to be addressed in order to improve response rates and ensure that the sample is truly representative of the broader population of manufacturing firms. For instance, in contrast to sectors where response rates were higher, the high abandonment rate in NAICS code 32 points to a need for targeted interventions, such as simplifying survey questions or providing additional support to participants. Additionally, the higher incidence of missing information in NAICS code 33 suggests that future research may benefit from incorporating more tailored data collection strategies to mitigate such challenges.

Therefore, understanding these sectoral differences is vital for developing tailored strategies aimed at increasing response rates and minimizing incomplete data. Accordingly, future research methodologies may need to be refined to address the unique characteristics of each sector, ensuring that a more balanced and representative sample is obtained in subsequent industrial research. These considerations are

critical for maintaining the rigor and validity of industrial research, as non-response and missing data can significantly impact the generalizability of the study's findings. Table 3 summarizes the results of the data collected according to the sample, illustrating the distribution of observations and response patterns across different sectors.

4. Results analysis and discussion

4.1. Research results

The analysis focused on environmental performance and the integration of IoT and AI technologies provides an expansive view into the digital sustainability efforts within Spanish enterprises. A Confirmatory Factor Analysis (CFA) was conducted to estimate the factor loadings of observed data onto the expected latent variables: 'Environmental Performance,' 'IoT,' and 'AI.' The results, detailed in Table 4, report mean scores, standard deviations, factor loadings with t-values, the square of the factor loadings (R²), composite reliability, and the variance extracted for each construct and its corresponding items. The construct of environmental performance, which integrates five distinct items, exhibits robust factor loadings and high composite reliability. Specifically, the composite reliability of 0.904 and the variance extracted at 0.729 for environmental performance indicate a consistent enactment of eco-friendly initiatives among the firms. Higher factor loadings for EP4 and EP5, related to product lifecycle management and green packaging, suggest these areas are well-embedded within company operations and significantly contribute to overall environmental performance metrics.

Regarding the technological aspects, both IoT and AI show composite reliabilities of 0.828, with a variance extracted of 0.648, indicating reliable application of these digital tools in the firms' operations.

Table 4
Variables estimation, factored loads and reliability analysis.

Construct/ Items	Mean (S. D.)	Factored load (t- value)	R ²	Composite reliability	Variance extracted
Environmental performance				0.904	0.729
EP1	4.500 (0.707)	0.765 (19.12)	0.565		
EP2	4.384 (0.834)	0.798 (20.16)	0.595		
EP3	4.392 (0.862)	0.811 (28.41)	0.666		
EP4	4.333 (0.956)	0.850 (37.78)	0.753		
EP5	4.341 (1.006)	0.830 (32.56)	0.721		
IoT				0.828	0.648
	4.044 (0.699)	0.713 (18.44)	0.472		
AI				0.828	0.648
	4.158 (0.684)	0.747 (18.96)	0.562		

All the factors loads are significant at level p < 0.01.

Table 3
Distribution of observations in terms of participation and size.

	Non-response		Response		Population
	Unanswered	Abandoned	Missing	Actual sample	All
# Observations	672	454	24	354	1504
# Employees	88	67	56	68	114
% NAICS - 31	29.59 %	33.33 %	33.21 %	33.05 %	31.59 %
% NAICS - 32	33.33 %	42.37 %	27.58 %	32.50 %	35.77 %
% NAICS - 33	37.08 %	24.31 %	39.50 %	34.45 %	32.65 %

Average scores of 4.044 for IoT and 4.158 for AI suggest notable adoption levels. However, modest R2 values imply the presence of other influential factors, potentially outside this study's scope, impacting the effective implementation of these technologies. These factors may include technological readiness, availability of technical expertise, and strategic integration within organizational goals.

Furthermore, the analysis suggests valuable insights into the categorization of Spanish firms within the digital sustainability framework proposed by Falcke et al. Evaluating the alignment of these firms with established digital sustainability strategies provides critical information regarding the effectiveness of such strategies across various industries. These findings contribute to a more nuanced understanding of the complex strategies required to mitigate climate change and highlight the importance of integrating digital innovation with traditional management practices in the pursuit of net-zero emissions. However, the disparity revealed by the analysis of the variables suggests that the degree of digital integration into environmental strategies varies significantly across firms. While some companies have successfully incorporated these technologies to enhance their environmental performance, others appear to lag. This disparity may be attributable to sector-specific challenges or varying levels of digital maturity. Therefore, it becomes necessary to further examine the characteristics of each industry and the organizational capacities that influence the successful implementation of digital tools for advancing sustainability goals. As shown in Table 4, the results provide systematic validation of the variables used to classify the firms, establishing a foundation for analyzing the intricate relationship between digital capabilities and the execution of environmental strategies.

4.2. Hypotheses discussion

4.2.1. Hypothesis 1 discussion: There is a positive relationship between the implementation of IoT technologies and improved environmental performance

The first hypothesis, which suggests a positive relationship between the implementation of IoT technologies and improved environmental performance, is well-supported by the empirical results. The Confirmatory Factor Analysis (CFA) highlights that IoT adoption is significantly linked to enhanced environmental performance metrics, such as reductions in energy consumption and improved resource management. Specifically, the high factor loadings for IoT-related variables, such as energy efficiency and predictive maintenance, indicate that firms adopting IoT achieve notable sustainability gains. The ability of IoT systems to monitor operations in real-time allows for quick adjustments to minimize inefficiencies, which aligns with the hypothesis that IoT adoption improves environmental performance. The composite reliability of 0.828 and variance extracted at 0.648 for IoT adoption suggest a robust application of these technologies across the sample.

Moreover, the results indicate that firms categorized as digitally enabled, which use IoT for reduction and removal strategies, are better positioned to achieve higher environmental performance. Specifically, 72 firms applied IoT to optimize energy consumption and emissions reduction, while 145 firms utilized IoT to enhance waste processing and pollution control. This demonstrates how IoT technologies help firms manage resources more efficiently and reduce environmental impact. Real-time data from IoT sensors enables firms to adjust processes as needed, supporting more sustainable practices. The results validate the hypothesis by showing that IoT adoption contributes to better environmental outcomes, particularly in resource-intensive industries where operational efficiency is key to sustainability. However, modest R2 values suggest other factors, such as technological readiness or firm strategy, may also affect the full realization of IoT's potential for sustainability improvements. The sectoral analysis reveals that IoT adoption varies across industries, with sectors such as food, beverage, and textile manufacturing (NAICS 31) showing higher engagement with IoT technologies. These sectors, characterized by high energy consumption

and resource-intensive operations, are more likely to benefit from IoT integration, as reflected by lower survey abandonment rates and higher overall participation. In contrast, sectors like chemical and plastics manufacturing (NAICS 32) displayed higher abandonment rates, potentially indicating sector-specific challenges in fully integrating IoT, such as complexity in processes or higher costs of implementation.

However, some firms (11) reported no measurable improvement in environmental performance despite using IoT technologies, indicating that successful IoT adoption depends not only on implementation but also on how well it is integrated into broader operational and environmental strategies. This underscores the need for firms to not only adopt IoT technologies but also ensure that they are aligned with their sustainability goals to maximize the potential benefits. Overall, the findings support H1 by demonstrating that IoT adoption contributes significantly to improved environmental performance, particularly through its capacity for real-time monitoring and optimization of processes. This reinforces the importance of IoT as a tool for driving sustainability improvements across various industries.

Hypothesis 2. (discussion: The adoption of AI-driven strategies significantly enhances environmental performance.) The second hypothesis, which proposes that the adoption of AI-driven strategies significantly enhances environmental performance, is substantiated by the empirical results. The CFA demonstrates that firms utilizing AI technologies, particularly in the context of predictive analytics and machine learning, experience notable improvements in their environmental performance metrics. Specifically, AI's ability to analyze large datasets, forecast trends, and optimize processes allows firms to address sustainability challenges proactively. The factor loadings for AI-related variables, such as energy use optimization and waste reduction, further support the hypothesis. With a composite reliability of 0.828 and variance extracted at 0.648, AI adoption appears to be a reliable and impactful tool for environmental management within the firms studied.

Firms categorized as digitally first, which prioritize AI in their reduction and removal strategies, are shown to have embraced AI's transformative potential. Out of the 233 firms identified as digitally first, 38 applied AI to enhance reduction strategies, focusing on optimizing energy consumption and reducing waste in production cycles. Furthermore, 67 firms utilized AI in removal strategies, developing innovative methods for carbon sequestration and environmental restoration. The results indicate that AI-driven approaches enable firms to go beyond process optimization by fostering new, data-driven solutions to reduce environmental impact. AI's predictive capabilities allow firms to anticipate environmental risks and adjust operations, accordingly, providing a proactive approach to sustainability management. Thus, the results validate the hypothesis, demonstrating that firms leveraging AI achieve greater improvements in environmental performance compared to those solely focusing on process enhancements through IoT. The findings also reveal that AI adoption varies across sectors, with heavy industries such as metal manufacturing and machinery (NAICS 33) showing the highest percentage of AI implementation, despite also displaying a higher percentage of missing information in the survey responses. This indicates that while firms in these sectors are exploring AI as a tool for sustainability, challenges remain in fully integrating AI systems into their operations. These challenges may stem from the complexity of AI technologies and the need for specialized expertise to implement and manage AI-driven strategies effectively. However, the firms that successfully integrate AI are better positioned to achieve long-term sustainability outcomes through advanced environmental monitoring, predictive maintenance, and resource optimization.

Conversely, some firms (128) reported little or no measurable impact from AI adoption, highlighting potential barriers such as organizational readiness, technological infrastructure, or insufficient strategic alignment with sustainability objectives. These findings suggest that while AI holds great promise for enhancing environmental performance, its full potential can only be realized when firms are equipped to leverage its advanced capabilities in a manner that aligns with their broader

environmental strategies. Overall, the results provide strong support for H2 by illustrating the significant impact AI-driven strategies can have on environmental performance. By enabling firms to move beyond incremental improvements, AI plays a critical role in driving more radical and transformative approaches to achieving net-zero emissions.

In summary, the results and their alignment with the proposed hypotheses provide insights into the varying levels of digital adoption and environmental performance across firms. The findings underscore the need for firms that have not yet integrated digital technologies to consider the potential sustainability benefits of IoT and AI. As digital tools become more critical for achieving net-zero emissions, firms must strategically evaluate their technological readiness and organizational capacities to maximize the potential of these innovations in advancing environmental sustainability. Table 5 offers a clear overview of the current digital sustainability strategies employed across the sample.

5. Conclusions

The examination of digital strategy implementation among Spanish manufacturing firms highlights the causal relationship between the adoption of IoT and AI technologies and their impact on environmental performance. The widespread use of IoT, with 228 firms actively incorporating these technologies into reduction strategies, underscores the connection between real-time data monitoring, operational efficiencies, and sustainability outcomes. The deployment of IoT for adjustments in energy consumption and predictive maintenance illustrates its role in optimizing processes and driving measurable reductions in environmental impact. IoT thus acts as a facilitator that enhances traditional operations, leading to improved resource conservation and lower emissions. This cause-and-effect relationship confirms the significance of digitally enabled strategies in achieving net-zero goals.

In contrast, although fewer firms (72 in total) have adopted AI in their reduction strategies, the impact of AI on environmental performance reflects a more strategic and long-term orientation. AI’s advanced capabilities in data analytics and machine learning enable firms to optimize existing processes while also forecasting future sustainability challenges and proactively implementing solutions. The use of AI signals a shift toward building digital-first strategies focused on low-emission models. While AI adoption remains less common than IoT, those firms using AI demonstrate an advantage in their ability to streamline waste reduction and optimize energy use. This reflects a more complex interaction between AI’s predictive capabilities and firms’ long-term sustainability objectives, suggesting that AI can drive more efficient processes. The gradual yet increasing integration of AI points to its potential as a valuable technology for enhancing environmental responsibility, particularly as firms grow more familiar with its complexity and application.

The category of firms with no digital involvement presents a different perspective. A small number of firms—three focusing on reduction and eight on removal—have maintained traditional methods without integrating digital technologies. This indicates either a delay in adopting digital solutions or a strategic decision to focus on conventional methods. Furthermore, 56 firms reported no significant use of digital technologies in their environmental strategies, highlighting substantial opportunities for these firms to explore digital integration to enhance sustainability efforts. The identification of 11 firms without notable

Table 5
Classification and Distribution of Digital Sustainability Strategies Among 354 Spanish Firms.

	Digitally enabled IoT: 228	Digitally first AI: 233	No Digital None: 67
Reduction	72	38	3
Removal	145	67	8
None	11	128	56

advances from IoT and 128 without substantial improvements from AI further underscores areas where digital applications could be expanded. This disparity emphasizes potential growth areas for AI and signals sectors where digital solutions could be applied more effectively to meet environmental goals. Table 6 summarizes the conclusion and categorization generated by the results analysis.

By analyzing the integration of digital strategies within Spanish manufacturing firms, the research reveals a preference for digitally enabled practices, especially those using IoT. Aligned with Falcke et al.’s framework, the findings suggest that net-zero strategies gain strong support when digital tools are embedded within established management practices. Among the 354 companies assessed, 228 have integrated IoT into their processes for reduction, reflecting a commitment to improving operational procedures through digital technologies. The use of IoT for real-time monitoring and predictive maintenance has become an established method for resource conservation and reducing environmental impacts, indicating a broader industry trend toward sustainability facilitated by digital innovations. Thus, When reflecting on the research question—*How do companies that align with digital sustainability strategies perceive the benefits of a net-zero approach, predominantly through the use of digital strategies?*—the study reveals that firms perceive IoT and AI as pivotal enablers for operational efficiency, resource conservation, and innovative sustainability solutions. Those who have

Table 6
Strategies and digital involvement framework.

Strategy	Digitally Enabled (IoT)	Digitally First (AI)	No Digital
Reduction	High involvement (228) in optimizing and enhancing existing processes to minimize environmental impact. Emphasizes the augmentation of operational efficiencies, possibly through real-time monitoring and adjustments in energy usage or predictive maintenance for resource conservation.	Moderate involvement (72) in creating new pathways to reduce environmental impact through innovative, technology-first solutions, such as AI-driven energy use optimization or waste reduction in production cycles.	Minimal use (3) suggesting that traditional reduction methods are less prevalent or less reported without the integration of digital technology.
Removal	Significant involvement (145) in directly eliminating environmental impacts, potentially through digitally enhanced remediation efforts like IoT-enabled pollution control systems or efficiency improvements in waste processing.	Substantial involvement (67) in pioneering removal strategies, potentially involving AI in developing new methods for carbon sequestration or other forms of environmental restoration and regeneration.	Lower occurrence (8), indicating either a lag in adopting digital technologies for removal or a focus on traditional removal methods.
None	Few instances (11) where digital technologies like IoT have not been applied or have not resulted in measurable changes in environmental performance, highlighting possible areas for further digital integration.	Predominant presence (128) where AI has not been used or has not led to significant changes in environmental performance, possibly indicating potential growth areas for AI application in sustainability initiatives.	Majority presence (56), indicating significant room for integrating digital technologies to enhance environmental strategies or areas where digital solutions may not be applicable.

adopted IoT technologies see tangible benefits in real-time monitoring and resource optimization, helping them gradually progress towards their net-zero goals. Similarly, AI-driven strategies allow companies to move beyond incremental gains, as AI facilitates more comprehensive, proactive environmental management approaches. However, the disparity between digital-first and digitally enabled firms suggests that companies are at different stages of realizing these benefits. The firms that have yet to embrace these technologies lag in their environmental performance, which indicates a need for broader digital adoption to fully leverage the potential of a net-zero approach. Ultimately, the study illustrates that aligning with digital sustainability strategies, whether through IoT, AI, or a combination of both, significantly enhances a firm's ability to move toward achieving net-zero emissions.

Nonetheless, the findings reveal a dichotomy: while a significant number of firms are advancing toward digital integration, a subset continues to rely on traditional methods without fully incorporating digital technologies into their environmental strategies. Firms with little or no digital technology use—particularly the three focusing on reduction and eight on removal—highlight areas where digitization could improve sustainability outcomes. Additionally, the identification of 11 firms with limited IoT integration and 128 without substantial AI use suggests opportunities for further development in digital applications. In line with Falcke et al.'s framework, the study confirms the critical role of digital technologies in supporting net-zero emissions and highlights the need for a comprehensive approach to climate change that integrates digital innovation with conventional management practices.

The analysis also underscores the limitations of firms that have not yet adopted digital technologies. The reliance on traditional methods among some firms—three in reduction and eight in removal—reveals the absence of digital tools needed to drive sustainability improvements. The lack of digital integration indicates that these firms may not benefit from the resource efficiencies and environmental gains that IoT and AI can deliver. This gap highlights missed opportunities to leverage digital technologies for enhanced environmental performance. Additionally, the identification of 56 firms with no substantial use of digital tools suggests a broader underutilization of available technologies, which may be due to barriers such as technological readiness or lack of alignment with strategic goals. These findings emphasize the need for greater digital adoption to close the performance gap between digitally enabled and non-digitally enabled firms.

Thus, the interplay between IoT and AI adoption and their effect on environmental performance supports Falcke et al.'s theoretical framework. The results show that firms integrating IoT and AI not only achieve operational efficiencies but also set a path toward long-term sustainability. While IoT provides immediate improvements by optimizing existing processes, AI introduces a strategic element that helps firms anticipate and manage future sustainability challenges. This complementary relationship—where IoT enhances current operations and AI supports forward-looking strategies—demonstrates the effectiveness of these technologies in achieving net-zero emissions. The causal link between digital adoption and environmental outcomes is clear: firms that invest in these technologies are better positioned to reduce their environmental impact and align their operations with global sustainability objectives.

In conclusion, the data demonstrate that digital technologies, particularly IoT and AI, are crucial to advancing environmental sustainability among Spanish manufacturing firms. The findings emphasize the causal relationship between the adoption of these technologies and improvements in environmental performance, with IoT driving immediate operational efficiencies and AI facilitating strategic decision-making for long-term sustainability. While many firms have embraced digital integration, a subset remains that has not yet fully utilized these technologies, indicating significant potential for future development. Ultimately, the study underscores the importance of an integrated approach to climate change that combines digital innovation with traditional management practices, fostering sustainable development

across industries and supporting progress toward net-zero emissions.

6. Implications, and future research

6.1. Theoretical implications

The findings of this study provide empirical evidence that contributes to the growing body of knowledge on digital net-zero strategies. The empirical data from this research reveal more nuanced insights into how strategies are adopted in firm-scenario contexts. The findings reveal that IoT is particularly effective in energy surveillance and predictive maintenance, which aligns with traditional operational practices, nonetheless it can offer measurable improvements in resource conservation and emission reductions. Furthermore, the study sheds light on the cautious yet growing adoption of Artificial Intelligence (AI) as a digital-first strategy. While Falcke et al.'s framework outlines the general advantages of AI in driving environmental strategies, this research highlights the incremental and deliberate approach firms are taking when integrating AI into their sustainability efforts. However, the moderate pace of AI adoption reflects the complexity of AI systems, the need for specialized expertise theory, and the alignment of AI-driven solutions with long-term strategic objectives. Unlike the IoT, which primarily refines existing processes, AI appears to be guiding a more transformative shift in corporate sustainability practices. As a result, this emergent trend points to the need for further refinement of theoretical models, as AI adoption does not simply follow the digital-first framework but represents a varied trajectory shaped by factors such as organizational readiness and industry-specific challenges.

Another insightful contribution is the suggestion that the path toward digital transformation is far from uniform. The empirical data present a dual narrative: one where IoT is widely adopted for enhancing current operations, and another where AI's full potential as a driver for new environmental strategies is still developing. This distinction offers fertile ground for theory development, as it exposes the differing routes companies may take in pursuing net-zero objectives. The divergence between IoT and AI adoption highlights the need for a more flexible theoretical approach that can account for the various stages of digital transformation, as well as the interplay between existing operational capabilities and the need for innovation.

Moreover, this study contributes original insights into the implications of digital servitization—where digital tools are integrated into service frameworks to enhance sustainability. For example, while the gradual incorporation of AI and IoT into manufacturing processes has been observed, this research goes a step further by examining how such technologies can transform service provision. The evidence suggests that companies utilizing digital technologies are not only improving their environmental performance but also creating value through more sustainable service offerings. Consequently, this expansion into digital servitization underscores a strategic shift where firms leverage technology to align with both market demands and environmental responsibilities. Thus, this study provides a deeper, more nuanced understanding of how digital technologies are shaping not only operations but also service models in pursuit of sustainability goals.

6.2. Managerial implications

Bearing in mind, the study offers critical insights for managers aiming to incorporate digital strategies into their environmental management systems. The findings highlight the significant role of IoT in enhancing operational efficiencies and improving sustainability outcomes. This indicates that IoT can provide a clear and actionable pathway for managers seeking to optimize energy consumption, improve resource management, and reduce emissions. Moreover, the widespread adoption of IoT in manufacturing processes demonstrates that the integration of such technologies is not only feasible but also yields measurable ecological benefits. To address this, managers must

take a proactive approach by critically assessing their existing processes and identifying areas where IoT can be effectively implemented to drive sustainability initiatives. Consequently, decision-makers should prioritize the integration of IoT within their operational frameworks to capitalize on its capacity to deliver real-time monitoring, predictive maintenance, and resource optimization. Furthermore, the evidence suggests that successful IoT integration can lead to enhanced environmental performance, providing firms with a competitive edge in an increasingly eco-conscious marketplace.

On the other hand, the cautious adoption of AI observed in the study underscores the complexity of its implementation. In this context, AI holds significant potential for driving innovation in sustainability strategies, but its adoption requires long-term planning, investment in specialized skills, and alignment with broader corporate objectives. As previously mentioned, AI should not be viewed solely as a tool for improving operational efficiency but rather as a strategic driver of environmental transformation. Thus, managerial teams must approach AI integration with a clear focus on how it can be leveraged to anticipate and address future sustainability challenges, fostering a culture of continuous innovation and ecological responsibility. In addition, the study identifies areas with minimal digital adoption, particularly among firms that have yet to fully incorporate IoT or AI into their operations. This is consistent with the broader trend of underutilization of digital technologies, which presents untapped opportunities for firms. Notably, managers must recognize the potential for digital tools to enhance sustainability efforts and develop strategies that facilitate their implementation. As a result, those firms that successfully integrate these technologies will not only meet sustainability targets but also position themselves favourably in a market that increasingly values environmental stewardship.

Moreover, the study emphasizes the importance of viewing digital adoption as a holistic process that integrates sustainability goals with overall business strategy. To sum up, successful digital integration requires more than the mere adoption of new technologies; it necessitates a fundamental shift in organizational culture towards embracing long-term ecological responsibility and fostering innovation. Ultimately, managers must lead this transformation by ensuring that their firms are well-prepared to meet both immediate and future sustainability challenges, leveraging IoT and AI as key enablers of environmental performance. In summary, the research provides a clear directive for managerial teams to not only embrace digital technologies but to strategically align them with the firm's environmental and business objectives. Therefore, by proactively integrating IoT and AI, managers can drive meaningful sustainability outcomes while positioning their firms for long-term success in a market increasingly driven by environmental considerations.

6.3. Limitations and future research

While this research provides valuable insights into the adoption of digital technologies among Spanish manufacturing firms, it is limited by its geographic and sectoral scope. Future research should seek to expand the study to additional regions and industries, allowing for a more comprehensive understanding of how digital strategies are being implemented across different contexts. Moreover, the focus on manufacturing sectors (NAICS 31, 32, and 33) highlights the need for comparative studies that explore how digital strategies are being adopted in other sectors, such as services or agriculture, which may present unique challenges and opportunities in the pursuit of net-zero emissions.

Additionally, this study raises important questions about the environmental costs of digital technologies themselves. The paradox of digital tools—such as the significant energy consumption associated with AI and IoT—warrants further investigation. Future research should explore how these technologies can be optimized to minimize their carbon footprint, ensuring that their contribution to sustainability is not

undermined by their resource-intensive nature. Addressing this paradox will be critical in advancing our understanding of how digital technologies can truly support net-zero strategies.

CRediT authorship contribution statement

Juan Carlos Monroy-Osorio: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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