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Overview

Environmental and governance strategies in ESG for industry 4.0: a systematic review

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Abstract: This study examined the integration of Industry 4.0 technologies with environmental, social, and governance (ESG) strategies to improve organizational sustainability and competitiveness. Industry 4.0 technologies, including blockchain, artificial intelligence (AI), the Internet of Things (IoT), and big data analytics, offer transformative capabilities for ESG reporting, resource optimization, and operational efficiency. By addressing sustainability challenges and advancing governance practices, these technologies enable businesses to meet their environmental and governance responsibilities while achieving economic growth. However, implementing Industry 4.0 in ESG frameworks presents challenges, such as high costs, poor data quality, and resistance to change. This paper analyzed existing literature to identify opportunities and barriers to aligning ESG with Industry 4.0, providing insights for managers, researchers, and policymakers. The report adds to the body of knowledge on sustainable innovation by pointing out the advantages and disadvantages of this integration. It also provides a roadmap for achieving sustainability-implementing goals over the long run in a rapidly evolving digital landscape.

Keywords: environmental; social and governance; ESG; sustainability; industrial revolution 4.0

1. Introduction

Over the past three decades, interest in ESG ratings and sustainable business practices has grown in academic and business circles. Various theoretical and analytical stances make it challenging to agree on how ESG practices and firm-level financial performance are related [1]. Adapting to global

economic challenges and maintaining long-term sustainability in the face of demographic and economic changes requires technology, improved public financial management, and modified financial mechanisms [2]. With smart manufacturing technology providing a potent tool for connecting operations with ESG goals, ESG sustainability is becoming increasingly significant in manufacturing. With data-driven decision-making and process optimization, manufacturers may improve labor conditions, lessen their environmental impact, and fortify governance procedures to position themselves for competitive and sustainable growth [3]. Larger organizations earn more from technology-enabled multi-sided platforms (MSPs), which boost environmental, social, and governance outcomes through digital operations, technology sharing, and flat management efforts [4].

By 2030, as the world aims for comfortable living in alignment with the Sustainable Development Goals (SDGs), good-quality ESG data will remain limited. IoT, AI, blockchain, and big data are famous Industry 4.0 technologies that enhance ESG reporting by reducing bias and errors and providing factual, clear, and real-time information [5]. These innovations are essential for better assessments of sustainability and the emerging practices of ESG. While smart manufacturing, defined by robotics, the Internet of Things, and AI, defines Industry 4.0, the integration of appropriate ESG indicators remains an issue. Addressing these gaps, including ESG issues, can enhance sustainable manufacturing development [6]. As Industry 4.0 brings business analytics to the environment, new opportunities arise for improving capital, energy, and supply chain management. Some issues remain, such as a lack of quality data and security, high cost of implementing solutions, and complex regulations. Important success factors include overcoming resistance, ensuring stakeholder engagement, and balancing short-term and long-term goals [7].

This study investigates the implicit themes of ESG strategies in the context of Industry 4.0 by performing a systematic review to identify the main research trends in this field. The following research questions are presented:

- How does integrating Industry 4.0 technologies enhance businesses' environmental, social, and governance (ESG) performance?
- What are the challenges and opportunities for companies in aligning ESG objectives with Industry 4.0 technologies?
- How does this convergence of ESG and Industry 4.0 affect organizational sustainability and corporate responsibility?
- What role does the Fourth Industrial Revolution play in reshaping ESG frameworks and reporting standards?

This study intends to advance current ESG strategy practices in the context of Industry 4.0 and identify research opportunities by thoroughly analyzing existing literature. Therefore, the paper will first lay the groundwork for comprehending the extent of the research, starting with an overview of the background of Industry 4.0 and ESG practices. The approach followed in performing this research will then be discussed. The report ends with a succinct synopsis of the most important findings.

2. Literature

2.1. Environmental, social, and governance (ESG)

ESG evaluates an organization's governance, social responsibility, and environmental performance to determine its sustainability and societal effects. Assessing how effectively a company achieves its sustainability goals requires accurate and trustworthy ESG data. However, obstacles exist in acquiring correct ESG data, with many corporations still reporting unreliable or biased information [5]. ESG performance is greatly influenced by digital transformation and triple transformation changes in people, business, and technology. When these changes are handled properly, strategic interactions between various elements can improve ESG outcomes [8]. Also, if such changes can be effectively managed, businesses can perform sustainably and, at the same time, enhance competitiveness [9]. The overall low voluntary compliance levels show the need for increased education and, thus, symbolic and rational action to efficiently tackle the new risks and responsibilities [10]. ESG focuses on the minimization of the adverse impact on the external community or environment, the cultivation of desirable behaviors through ethical standards, and the optimal use of resources. It is essential to mitigate industrial incidents and stimulate social constructiveness, including increased corporate transparency [11].

ESG integration into investment strategies increases overall financial stability by reducing the overall risk, particularly the tail dependence between sectors and stock exchanges, and diminishing the risk spillover effect, especially in intelligent infrastructure and final frontier industries [12]. With sustainability remaining a top priority for companies, these are increasingly announcing their ESG commitments to meet all 17 SDG goals set forth by the United Nations. The focus of companies on environmental, social, and governance (ESG) is growing to guarantee corporate accountability in addressing these aspects [13]. A company's competitiveness and sustainability can greatly increase by implementing strong ESG policies addressing global issues, including inequality, climate change, and ethical governance [14]. Maximizing resource use through enhanced ESG performance supports product differentiation. This impact is particularly notable in less-developed economies or in sectors with stricter laws, such as the technology industry. While ownership structure and other factors also influence this relationship, there is strong evidence that good ESG practices are key to innovation [15]. The integration of governance structures can significantly influence how companies leverage Industry 4.0 innovations to achieve circular economy objectives and broader sustainability goals [16].

2.2. Environmental, social, and governance (ESG) and Industry 4.0

The application of Industry 4.0 technologies makes it easier to encourage innovation, implement more sustainable solutions, and increase resource utilization. This enhances ESG performance when green servitization strategies and sustainable supply chain management (SSCM) are integrated to help businesses transition toward a green and sustainable-oriented business model (GS-OBM). Technology and, particularly, corporate governance further improve this alignment in the modern world, thus providing businesses with a competitive edge and assisting in attaining sustainability goals. Innovation focused on sustainability depends on a combination of in-house technological strengths and external governance support, aligning with the strategic application of ESG principles to secure enduring

competitive benefits [17]. Many organizations require information to adhere to governance regulations, encourage and enhance social responsibility, and achieve operational efficiency through digital technology. Industry 4.0 technologies enhance environmental relevance by reducing human-disrupted risks in sectors such as mining and by optimizing resource efficiency [11]. The natural resource-based view and dynamic capability theory support the argument that Industry 4.0 enables firms to strengthen their green business strategies with the right governance structures [18].

The industrial revolution marked the beginning of significant greenhouse gas emissions, threatening the future economy, society, and environment [10]. Examples of Industry 4.0 technologies that can enhance ESG include IoT and AI, which reduce operational risks, maximize resource use, and increase environmental sustainability. These technologies encourage improved governance and social responsibility by boosting the effectiveness and transparency of business operations [19]. Industry 4.0 technologies like smart infrastructure use ESG to improve investment stability and lessen risk spillover. Together, these industries build more robust and durable financial markets [12].

Industry 4.0 technologies promote ESG goals by increasing operational efficiency, data credibility, and openness. These technologies enable real-time data collection and credible ESG reporting; still, they present challenges such as a lack of emergence and worker readiness. This is explained by integrating ESG principles into smart city logistics, which requires the simultaneous development of technical solutions [5,20,21]. This research adopts the natural resource–based perspective alongside the dynamic capabilities theory to explore the role of Industry 4.0 in advancing environmentally sustainable business approaches [18]. It emphasizes that innovation focused on sustainability depends on a combination of in-house technological strengths and supportive external governance structures, aligning with the strategic application of ESG principles to secure enduring competitive benefits.

To outline crucial research fields and missed opportunities in ESG activities within the context of Industry 4.0, this paper performs a systematic literature review (SLR) to build knowledge in the field. The paper reviews earlier studies to provide relevant information to organizations wanting to align technology with ESG goals. Moreover, it notes barriers to adoption and ways to leverage Industry 4.0 to improve sustainability and corporate accountability initiatives. This study aims to assist in detailing how technology might aid in the accomplishment of sustainability goals and point out existing research gaps. Research findings provide valuable suggestions for scholars, industries, and governments as they grapple with the multiple opportunities and risks of integrating Industry 4.0 technologies with ESG to achieve sustainability and competitiveness in the long run.

This conceptual framework maps specific Industry 4.0 technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), blockchain, big data analytics, and cyber-physical systems against the three pillars of ESG (environmental, social, and governance). This approach (Table 1) allows for a more systematic and targeted evaluation of how each technology contributes to ESG:

- Environmental management: including emissions reduction, energy efficiency, waste minimization, and climate adaptation.
- Social impact: labor safety, transparency, stakeholder engagement, and data ethics.
- Governance innovation: including compliance automation, traceability, decision-making, and performance reporting.

Table 1. Mapping of Industry 4.0 technologies to ESG components.

Technology	Environmental impact	Social impact	Governance impact
IoT	Real-time energy and emissions monitoring	Workplace safety via sensors	Automated compliance and audit trails
AI	Optimized resource usage and predictive maintenance	Personalization and customer-centric design	Data-driven governance insights
Blockchain	Carbon tracking, supply chain transparency	Ethical sourcing verification	Tamper-proof ESG reporting and accountability mechanisms
Big data analytics	Environmental risk forecasting	Social sentiment and stakeholder analysis	Strategic ESG decision support
Cyber-physical systems	Intelligent waste and emissions control	Human-machine collaboration and skill enhancement	Operational governance via system-level feedback loops

3. Methodology

A systematic review is a critical and methodical summary of existing literature on a specific research theme or clinical question. It follows a systematic approach [22].

3.1. Database selection

Web of Science and Scopus are two of the most prominent and competitive citation databases worldwide. Both databases are frequently used in studies pertaining to meta-analyses. Citation databases are particularly utilized in fields connected to health and medical science and the more conventional fields of information science and library science [23]. This study employs both Scopus and WOS databases.

3.2. Article selection

Figure 1 summarizes the steps involved in conducting a systematic literature review. A thorough search using previous literature, threshold, dictionaries, and related terminology yielded the keywords search string (Table 3). Environmental, social, governance, and Industry 4.0 form the basis of knowledge. By using similar terms and synonyms associated with ESG and Industry 4.0, relevant search strings were used to classify keywords based on search criteria. “Environmental, Social, and Governance”, “ESG”, “Industry 4.0,” and “Industrial Revolution 4.0” were among the primary terms. Table 3 displays the search string used. A total of 57 articles were obtained by considering all manuscripts available in the chosen databases. After screening the manuscripts to make sure they were relevant to the integration of ESG and Industry 4.0, duplicate entries, particularly those from multiple databases, were removed to prevent redundancy, and manuscripts were further selected based on their originality, relevance to the research scope, and focus on the alignment of ESG practices with Industry 4.0 technologies. This process included studies that provided insightful information about the

intersection of these domains, and the final selection comprised 18 articles. The systematic review followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol to ensure methodological transparency and replicability, as shown in Figure 1. 59 records were identified through Scopus (n = 31) and Web of Science (n = 28). After removing two duplicate records, 57 articles were screened based on their titles and abstracts. During this stage, 32 records were excluded due to irrelevance, primarily because they did not directly address ESG or Industry 4.0 technologies.

Of the remaining 25 articles, two full texts could not be retrieved. The 23 articles that remained were assessed for eligibility. During the full-text review, 5 articles were excluded because they lacked a clear connection to ESG principles, either focusing narrowly on digital technologies without linking them to environmental, social, or governance outcomes or presenting broad ESG discussions without substantial mention of Industry 4.0 technologies. Finally, 18 studies were included in the review. Inclusion and exclusion criteria are clearly mentioned in Table 2.

Table 2. Inclusion and exclusion criteria.

Inclusion	Exclusion
Articles explicitly addressing ESG and at least one Industry 4.0 technology	Conference abstracts, editorials, or non-peer-reviewed sources
Peer-reviewed journal publications Empirical or conceptual research Published between 2010 and 2026 English language	Articles not directly connecting ESG and I4.0 Duplicate or inaccessible full texts

All keywords and Boolean operators included in the search string across the chosen academic databases (Scopus and Web of Science) are given in Table 3 to make sure that the process used for reviewing is open for others to follow and understand.

Table 3. Search string in WOS database.

No	Keywords	Justification
1	‘‘Environmental social, and governance’’ OR ‘‘ESG’’ OR ‘‘Environmental SG’’	To identify literature related to environment, social issues, and governance.
2	‘‘Industry 4.0’’ OR ‘‘IR 4.0’’ OR ‘‘Industrial revolution 4.0’’	To identify literature related to Industry 4.0.

Article classifications:

The primary research streams examined in this study were identified using systematic classification by PRISMA. The articles’ alignment of Industry 4.0 technology with ESG goals led to their refinement and categorization into discrete categories. The bibliographical list is described in Figure 1, displaying the methodical article selection and review process. The three main research streams from this classification are ESG performance and corporate innovation, Industry 4.0 and sustainable practices, governance, regional focus, and strategic investment. These streams give

researchers, managers, and policymakers valuable insights and a basis for comprehending the opportunities and difficulties in integrating Industry 4.0 with ESG goals. A structured bibliographical list was created to categorize the chosen manuscript's research stream and focal area. Table 6 presents an analysis and summary of the findings. Three primary research streams were used to categorize the publications.

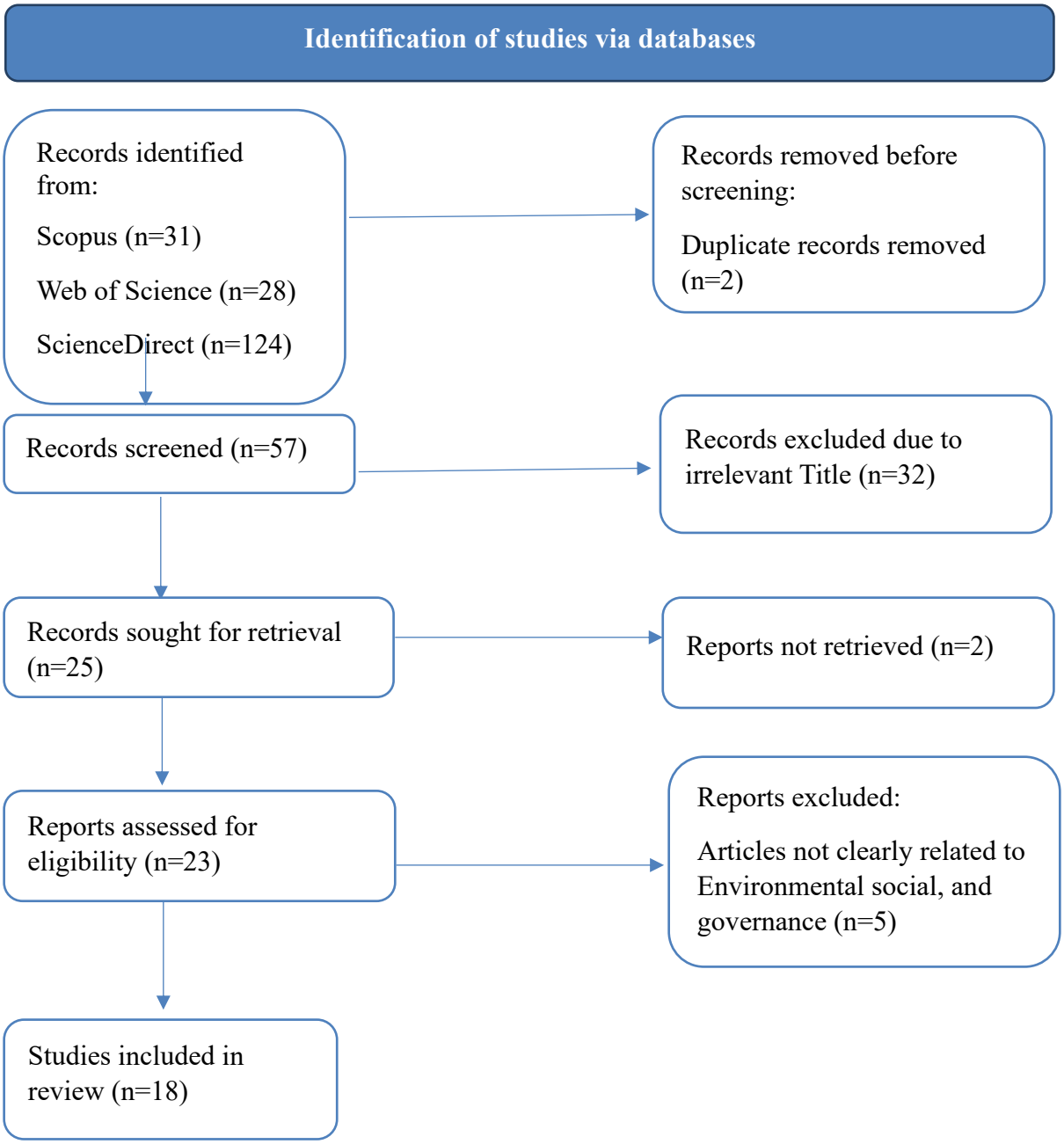

Figure 1. Flow diagram of study selection.

4. Results and analysis

The results indicate that most of the research was conducted in Asia (Table 4). China recorded the highest number of studies (5 studies), followed by India (2 studies), the UK (2 studies), Italy (2

studies), and Germany (2 studies). Finally, Thailand, Malaysia, Kuwait, Australia, and South Korea each had one study. Table 5 maps out the distribution of existing research on the chosen topic across various scientific journals.

Table 4. Geographical location of publication.

Country	Number of studies
China	5
India	2
UK	2
Italy	2
Germany	2
Other	5
Total	18

Table 5. Leading journals in the current review.

Journal	Number of studies
Technological Forecasting and Social Change	1
Business Strategy and the Environment	2
Clean Technologies and Environmental Policy	1
Grenze International Journal of Engineering and Technology	1
Journal of the Knowledge Economy	1
Corporate Social Responsibility and Environmental Management	1
Journal of Risk and Financial Management	1
Sustainability	1
Technovation	1
Journal of Emerging Technologies in Accounting	2
Economic Development and the Environmental Ecosystem	1
Journal of Environmental Management	1
Sage Open	1
Computer Science	1
Energies	1
Journal of Business Research	1
Total	18

Table 6. Summary of studies on ESG in the Era of Industry 4.0.

No	Author	Sample and country	Main findings	Method
1	[24]	ESG ratings and green patents of a Chinese firm (Germany)	Clean technology innovation and corporate ESG performance are strongly correlated, and this relationship is strengthened by organizational scale, digital transformation, and environmental concern.	Empirical analysis of ESG on cleantech innovation
2	[20]	268 responses from both manufacturing (187) and service firms (81) (Malaysia)	Industry 4.0 technology adoption enhances organizational sustainability and competitiveness. It supports ESG practices by driving innovation, efficiency, and responsible governance.	Partial least squares structural equation modeling (PLS-SEM)
3	[25]	N/A (China)	By increasing sustainability and productivity, Industry 4.0 technologies have the potential to significantly enhance the food agriculture sector.	PRISM framework
4	[26]	Companies in various industry sectors in the UK	Strategic investment in corporate transformation toward Industry 4.0 (CTTI4.0) has grown across industries, benefiting financial performance. Companies with high ESG performance are more likely to make CTTI4.0 disclosures and achieve better results.	Textual analysis with quantitative methods
5	[2]	Data from 2000 to 2023 were used for OECD nations, including the US, Japan, Sweden, and Germany	Pension systems must adapt to technology improvements, demographic shifts, and economic crises by implementing sustainable financial mechanisms and improving public financial management.	Mixed-methods
6	[1]	Euro Stoxx 300 index (Italy)	Environmentally friendly corporate policies boost profitability and pose trade-offs across environmental, social, and governance dimensions.	Dynamic panel model
7	[27]	Italian manufacturing sector (Italy)	Through predictive maintenance, waste reduction, and optimal resource use, AI-assisted big data analytics (BDA) is a vital component of Industry 4.0's advancement of strategic sustainable development (SSD), promoting innovation, efficiency, and sustainability.	N/A
8	[15]	A-share listed companies in China	Higher ESG efficiency positively correlates with increased corporate innovation, with ownership structure moderating the relationship, with adverse effects more noticeable in less developed economies or stringent environmental restrictions.	Empirical research approach
9	[9]	ESG reports of 280 global energy companies (Thailand)	The triple transformation of business, people, and technology positively impacts ESG performance; the situation and the interactions between drivers and mechanisms shape the results.	Fuzzy-set qualitative comparative analysis (fsQCA) and structural equation modeling (SEM)
10	[28]	Disruptive technology sectors (China)	The C-vine model emphasizes how dependent intelligent infrastructure is on important industries and how ESG integration lowers risk spillovers, especially in infrastructure and security.	Copula-based approaches, including C-vine and t-copulas, to model dependence and risk spillover

No	Author	Sample and country	Main findings	Method
11	[5]	Multiple countries with data from global case studies (India)	Industry 4.0 technologies enhance ESG data accuracy, transparency, and dependability, addressing consumer concerns about data reliability and eliminating biases in self-reported data for informed sustainability assessments.	Literature review, conceptual model development, and framework analysis.
12	[29]	N/A (India)	Industry 4.0 technologies and green practices positively impact green supply chain performance and servitization, with green servitization mediating the relationship and ESG compliance being moderated.	Structural equation modeling (SEM)
13	[17]	FTSE companies (Kuwait)	Industry 4.0 technology enhances the integration of green servitization innovation into green sustainable supply chain management practices, fostering collaboration between industry and corporate governance institutions.	Mixed-methods
14	[30]	Data collection from 28 companies in 8 sectors (Australia)	By combining ESG and AI into one practical framework, investors can more easily and effectively assess how responsibly companies use AI, filling essential gaps in transparency, governance, and risk management.	Collaborative research methodology
15	[12]	Chinese energy companies (China)	The accuracy and dependability of environmental disclosures are hampered by the infrequent and intricate procedures of current ESG reporting techniques, which are inadequate.	Environmental reporting system
16	[13]	Korean companies (South Korea)	Korean businesses place high priority on protecting consumers, especially when it comes to digital human rights. Korean corporations' efforts to form international relationships, as highlighted by the SDGs, were noticeably lacking.	Text mining approach
17	[31]	Manufacturing companies (China)	By directly increasing productivity and indirectly influencing ESG performance, with social performance mediating and environmental performance reducing the effect, digital transformation raises corporate TFP.	Fixed-effect model and staggered difference-in-differences (DID) method
18	[18]	Companies from the FTSE All-Share Index for the period 2012–2021 (UK)	Dynamic capabilities, technological innovation, and governance mechanisms define how production planning and green strategic investment decision-making methods affect business success.	Mixed-methods

5. Findings and discussion

The research question guides the presentation of the findings. The core research streams from the 18 studies form the basis of the debate. These lines of inquiry also point to the primary and secondary problems in the age of Industry 4.0. To help maintain consistency with the study's purposes, the findings are arranged to relate to the themes identified during the systematic review of the literature. These technologies improve the quality of ESG data by enabling accurate and timely monitoring, maintenance, automatic rule application, and transparent reporting [12]. Through these capabilities,

companies can optimize resource usage, reduce emissions, and establish traceable governance mechanisms, thereby reinforcing sustainable and responsible business practices [32].

Integrating ESG principles with Industry 4.0 technologies presents numerous challenges, including high implementation costs, limited technical capabilities, data privacy concerns, and organizational resistance to change [33]. This synergy encourages the development of circular economy practices and resilient corporate governance structures that are responsive to both environmental imperatives and social responsibilities. The impact is particularly evident in regions and industries that face stricter regulatory environments or societal scrutiny, where the strategic deployment of digital technologies crucially encourages ESG performance and reporting credibility. ESG frameworks are being transformed by the Fourth Industrial Revolution, which makes precise, automated, and verified reporting accessible, conforming to shifting international sustainability reporting standards [28].

5.1. Research stream 1: ESG performance and corporate innovation

Identifying strategies for facilitating the shift to renewable energy, considering the global mandate to create an economic paradigm that balances environmental protection with growth, is critical. Increased ESG efficiency results in more creativity. The company's ownership structure moderates the relationship between corporate innovation and ESG efficiency [1]. Areas with stricter environmental rules or less economic development exhibit substantial adverse moderating effects of ownership [15,24]. Financial performance benefits from the corporate transition to Industry 4.0 transparency. The relationship between financial performance and corporate transformation toward Industry 4.0 (CTTI4.0) disclosure is moderated by ESG policies; companies that perform better in these areas typically also have higher levels of CTTI4.0 disclosure and greater financial performance [26].

Standards for ESG reporting have been issued by numerous nations, particularly for businesses with high degrees of pollution. Investors, the public, and other external stakeholders now primarily learn about firms' environmental effects through ESG disclosure [12]. With the growing awareness of the detrimental impacts of corporate operations on the environment and society, consumers, investors, and regulators have become more interested in ESG issues [9]. Depending on the circumstances and how drivers and processes combine, change benefits ESG performance. One crucial element that connects improved innovation capabilities to ESG practices is ESG efficiency. In terms of ESG performance, companies that can successfully manage the opportunities and challenges of triple transformation are likely to perform better than their rivals [9,15]. Resource management, pollution reduction, and global warming adjusting are all significantly enhanced by technologies associated with Industry 4.0, such as generative artificial intelligence (AI), the Internet of Things (IoT), and big data analytics. These advances facilitate predictive maintenance, allow for precise, continuous evaluation of environmental parameters, and lower pollution and waste through more intelligent decision-making. Particularly, digital green supply chains encourage collaboration between organizations, which catalyzes environmental innovations and sustainable business practices. This enables businesses to work collaboratively to minimize their ecological impact and improve their compliance with environmental laws [32].

Corporate ESG performance, which is impacted by variables including company size, digital transformation, and environmental regulations, propels the development of clean technologies. Its influence is especially notable in industries with high pollution levels, and it is essential for promoting green transitions and environmental improvements. ESG practices are crucial for supporting the switch to renewable energy sources and coordinating corporate expansion with sustainability, regardless of the ownership structure [24]. Industry 4.0 technologies improve data completeness, efficiency, and dependability by enabling real-time, precise reporting [5]. Increased transparency addresses intricate environmental metrics to enhance sustainability and assist stakeholders in making decisions [30]. The basis for sustainable business operations and efficient corporate environmental management is strengthened by streamlined ESG reporting [12].

5.2. Research stream 2: Industry 4.0 and sustainable practice

The industrial environment has undergone a radical change in the era of Industry 4.0 due to the convergence of digitalization, artificial intelligence (AI), and big data analytics (BDA). Integrating the physical, virtual, and digital environments referred to as Industry 4.0 has created novel, impossible advancements in data science and technology [27]. The Fourth Industrial Revolution analyzes how ESG integration influences investment decisions across the technology stock categories. Sustainability is assessed in terms of ESG. From all Industry 4.0 technologies, real-time data, data authenticity and prediction, transparency, and structured data could address this challenge [5,25].

ESG compliance weakens the relationship between Industry 4.0, green practices, and green supply chain (GSC) performance, but enhances the positive relationship between Industry 4.0, green practices, green servitization, and GSC performance. However, by adopting green servitization innovation projects, firms can improve their revenues and customer satisfaction, serve multiple markets, and create value across the network and value chains [17,29].

5.3. Research stream 3: governance, regional focus, and strategic investment

Business sustainability and competitiveness in the face of growing ESG concerns depend on adopting technologies to address industrial difficulties and governance issues. ESG practices significantly increase a company's competitiveness. Investments in staff training and the start of technology transfer across firms are essential for the environmentally and socially appropriate adoption of Industry 4.0 technology. This will provide businesses with the skills and information they need to use IR4.0 technology to improve ESG practices and competitiveness [20]. Because sustainability is important, companies must declare their ESG goals. Maximizing the expenses of funding social security requires raising the bar for public financial management and the quality of public services in this area. Utilizing technological improvements is also crucial to lowering the threats that Industry 4.0 presents [2,13].

The absorptive and adaptive capabilities of boardrooms, the ability to generate and collaborate on knowledge, the adoption of technology, and corporate governance mechanisms have shaped the current production planning and green strategic investment decision-making practices (GSIDMP) in large companies [18]. Future security and communication industries will gain from ESG's reduction of reliance, especially tail dependence, between the IT sector and the stock market. The implementation

of Industry 4.0 in the food agriculture industry is anticipated to revolutionize and galvanize food production to increase the efficiency of the industry's output and to match, in tandem, a country's gross domestic productivity, given the anticipated colonization of human daily life by artificial intelligence, including in industry productivity [17,25].

6. Implications

6.1. Theoretical implications

A new way to evaluate corporate sustainability combines Industry 4.0 technologies and ESG frameworks. The necessity for theoretical frameworks that tackle the intricacies of digital transformation in sustainable contexts is highlighted by this integration, which improves governance and decision-making models [9]. Sustainability outcomes emerge from the interaction between AI-driven digital transformation and ESG business activities. To ensure the long-term viability of the models, theoretical models need to incorporate ways in which these technologies could detect social problems and avoid the occurrence of catastrophes in the environment [34]. Predicted advancements in the Industry 4.0 sectors, especially in the manufacturing sector, would enable various sectors to assess and report on environmental, social, and sustainable criteria based on the current theoretical discourses. This calls for research into of how data-driven approaches can enhance transparency in sustainability reporting [28].

One of the promoting areas of circular economy is Industry 4.0, where resources are used and recycled responsibly. One of the practical implications is that new theoretical models need to be developed to reflect the real-life processes of resource optimization and sustainable production principles. Adopting high ESG standards reduces stock returns, particularly in the energy sector. This suggests a theoretical relationship between economic performance and ESG processes, especially the need for further research on the effects of sustainability measures on financial outcomes [9]. The confluence of ESG factors and Industry 4.0 technologies disrupts old environmental sustainability frameworks through a more technologically complex and dynamic management of the environment [26]. Popular theories in ecological management have focused on gradual thrusts through organized measures like cutbacks on waste and expansion of resource efficiency. However, the potential of technologies like real-time data analytics, AI, IoT, and blockchain in Industry 4.0 makes it possible to make real-time decisions, thus fundamentally changing the way the environment's performance is monitored. Old environmental management models must be reevaluated to make room for Industry 4.0 technologies.

Additionally, the models of environmental management, which have conventionally relied on artificial interference and compliance with controls, need to change to meet the challenges of the capabilities of Industry 4.0 [26]. Adopting digital solutions to supply chain management, which promotes more transparency and efficiency in operations, necessitates that these organizations adopt a more sophisticated type of governance [35]. Since AI and automation drive these frameworks, changes may be necessary to include data-informed decision-making and automation of compliance checks.

6.2. Managerial implications

ESG laws and Industry 4.0 interact significantly with management practices. As can be seen, convergence poses challenges and opportunities that managers must tackle if growth and competitive advantage are to be achieved. Industry 4.0 technologies and ESG regulations affect the objects and processes used in management decisions. To meet ESG targets, organizations must align with technologies such as IoT, AI, blockchain, and big data. These tools support real-time and clear data disclosure, enhance organizational operations and decision-making, and help achieve strategic and sustainability goals [36]. Generating more value from resources while minimizing the consumption of resources is the primary way by which Industry 4.0 technology promotion encourages innovation in green practices and servitization. Managers should fund these technologies to champion environmentally responsible supply chain practices and differentiate themselves in markets that increasingly address sustainability problems [37]. Workforce development is also important because when the transformation is digitized, so are the operational processes. There is also a challenge for managers to engage in efforts to ensure that the employees receive the required training, especially in properly utilizing the Industry 4.0 tools. This helps overcome resistance to change while ensuring that ESG targets are met.

In the same context, to solve cybersecurity threats, costly implementation, and the challenge of rather complex ESG reporting requirements, transparency and governance are paramount and require useful platforms. The demand from stakeholders for accurate and reliable ESG data cannot be overstated. To gain the support of stakeholders, including investors, consumers, and regulators, managers need to communicate ESG actions and outcomes simply and concisely to guarantee that they align with social and environmental goals [38]. Another factor is the relationship between operations and near-term versus long-run commitments. Managers can ensure that their companies stay competitive and adaptable in a changing business environment by incorporating ESG concepts into strategic planning and encouraging a sustainable culture. There is evidence that businesses will be able to attend to the increased demand of the stakeholders and regulatory agencies [39]. For practical application, this review outlines a structured roadmap to implement technologies from Industry 4.0 to help protect the environment. Managers should first carry out an environmental evaluation and then pick appropriate technologies to meet their environmental objectives. Cloud-based IoT is an ideal solution for SMEs to grow, but bigger firms could concentrate on fully integrated smart technology.

7. Limitations

There are many limitations to this study. First, it focuses on integrating Industry 4.0 technology with ESG initiatives, yet it may have missed pertinent material because of keyword selection. Despite efforts to incorporate relevant phrases like “ESG”, “Industry 4.0”, and “sustainability”, it is possible that studies that used other terminologies or frameworks that were not specifically associated with these keywords were overlooked. Essential insights from different fields or larger contexts may have been left out. Most of the material used in the review comes from the well-known sources Web of Science and Scopus. Despite the thoroughness of these databases, it is still possible to overlook

necessary research published in specialized journals or less common sources. These papers may offer more viewpoints on the difficulties and possibilities of integrating ESG with Industry 4.0.

Second, although this publication summarizes previous research, it skips over primary or empirical data. The range of conclusions is constrained by the use of secondary data and a systematic review approach, particularly regarding case studies and practical implementations of Industry 4.0 technologies in ESG frameworks [40]. Lastly, the study acknowledges that incorporating cutting-edge technologies into sustainable practices is inherently challenging. Stakeholder resistance, disparities in technological adoption across industries, and varying non-financial reporting standards are among the issues that are recognized but not fully addressed. To provide practical answers, future studies should investigate these issues in greater detail [33].

8. Future research avenues

Future studies should examine how Industry 4.0 technology can be combined with ESG policies to increase sustainability and operational effectiveness. These investigations are crucial to identifying the capacity of big data analytics, artificial intelligence, and the Internet of Things to improve ESG reports and performance. IoT devices enable real-time data collection for ESG compliance., while big data analytics can process complex datasets to evaluate environmental impacts and improve ESG assessments. In using AI, the concern is covering patterns in large datasets to make the correct predictions on ESG compliance [5].

It is also essential to look at the opportunities and risks of adopting these technologies in various organizations. Considering these issues will result in possible ways of dealing with adoption issues, such as high costs, lack of technical knowledge, and resistance to change. Research can also aid in defining how such Industry 4.0 technologies can be integrated into current ESG frameworks to guarantee the compatibility of additional technical gains with sustainable aspirations. Further research should focus on developing better-functioning ESG initiatives to support sustainable development in various sectors and industries [9]. The adoption of technology for environmental sustainability is significantly facilitated by government support, since funding may improve the impact of technology for green entrepreneurship through the development of knowledge management directions. With such support, it is possible to link Industry 4.0 to ESG by addressing issues like high expenses, low awareness, and resistance to change [41].

9. Conclusion

Combining Industry 4.0 technologies such as big data, blockchain, the Internet of Things (IoT), and artificial intelligence (AI) transforms how companies consider sustainability. These technologies enhance ESG performance by making it feasible to collect data instantaneously, making reports more accurate, and rendering resource management more effective. These advancements enable companies to fulfill their ESG duties more transparently and effectively.

However, the path to incorporation is not without challenges, such as high implementation expenses, technical challenges, and data security concerns. Nevertheless, potential opportunities for innovation, improved decision-making, and improved confidence among stakeholders balance the

drawbacks. When properly executed, such innovations provide a closer link between business operations and moral, ecological solutions.

In the future, traditional ESG frameworks must shift to stay in line with Industry 4.0's digital transformation. Basic or retrospective reporting models are no longer sufficient. However, frameworks designed to support proactive environmental sustainability assessments that are continually evolving and automated are becoming more essential. Additionally, it is strategically vital to address the gap between ESG objectives and technological advancement, but it is also necessary to develop more accountable, adaptive, and ready-for-growth businesses.

Use of AI tools declaration

We have not used artificial intelligence (AI) tools to create this article.

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Conflict of interest

The authors declare no conflicts of interest related to this research

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