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INDUSTRY 5.0 AND ITS ROLE IN ADVANCING ESG AND SDG PRINCIPLES: A SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

Even though Industry 4.0 offers widespread automation across various technologies, the question remains whether the industrial evolution is over. In recent years, the term Industry 5.0 has been used to represent human-centric and sustainable industrial practices, which align with achieving the environmental, social, and governance (ESG) principles outlined by the United Nations (UN). These principles serve as a framework through which companies can contribute to fulfilling the UN's global Sustainable Development Goals (SDGs). Given the growing significance of Industry 5.0 in the context of sustainability, this study seeks to explore two key research questions: (1) „What is the current state of research on Industry 5.0 in relation to ESG and SDGs?" and (2) „What thematic areas are most commonly explored in research linking Industry 5.0, ESG and SDGs?". To answer these questions, a systematic literature review was conducted, analysing a final selection of 22 papers. Three main clusters were identified, categorizing the studies as follows: (1) Management and Sustainability, which examines sustainability management practices and the role of ESG factors in business; (2) Technology and the Human Factor, highlighting the intersection of technological and social innovations; and (3) Digital Innovation and Future Technologies, encompassing emerging technological trends such as Blockchain, Artificial Intelligence (AI), the Internet of Things (IoT), and the metaverse. This study highlights the importance of strategic planning, circular economy integration, and digital transformation in fostering sustainability. While the research on Industry 5.0 is still evolving, this study provides insights into the intersection of automation, human-centricity and environmental responsibility.

KEYWORDS: *Industry 5.0, ESG, SDGs*
JEL CLASSIFICATION CODES: *M14, O33, Q01*

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INTRODUCTION

The industrial landscape has long been transformed by the advancements associated with Industry 4.0, which is characterized by widespread automation and digitalization. Recently, however, attention has shifted toward Industry 5.0 – a paradigm that emphasizes the reintegration of human-centric processes alongside technological innovations (Breque et al., 2021). In parallel, environmental, social and governance (ESG) principles have emerged as an essential framework for guiding responsible business practices, and the United Nations' Sustainable Development Goals (SDGs) provide a global benchmark for achieving sustainable development (United Nations, n.d.a). Despite the individual prominence of these fields, the literature examining the interrelationships between Industry 5.0, ESG and SDGs remains relatively nascent and fragmented.

As industries worldwide transition towards more sustainable and resilient business models, understanding the linkages between Industry 5.0 and sustainability frameworks becomes increasingly critical. Industry 5.0 not only enhances the efficiency and automation introduced by Industry 4.0 but also integrates ethical, environmental and social considerations, ensuring that technological advancements align with long-term sustainability objectives (Zizic et al., 2022). ESG principles play a crucial role in guiding responsible corporate governance, investment strategies and stakeholder engagement (Rau & Yu, 2024), while the SDGs provide a globally recognized roadmap for sustainable development (United Nations, n.d.a). By examining the interplay between these three domains, this study aims to uncover how Industry 5.0 can serve as an enabler of ESG and SDGs, contributing to a more sustainable and human-centric industrial transformation. The findings are particularly relevant for policymakers seeking to design effective sustainability regulations, business leaders aiming to integrate Industry 5.0 technologies into corporate ESG strategies, and scholars advancing research at the intersection of technology and sustainability.

Therefore, a systematic literature review was conducted to identify the main thematic areas that underpin the relationships among these domains and to offer insights into how Industry 5.0 can act as a catalyst for sustainable development.

THEORETICAL BACKGROUND

Industry 5.0

Industry 5.0 has emerged as a transformative paradigm that builds upon the technological advances of Industry 4.0 while integrating a broader spectrum of innovations – from digital connectivity to bioengineering – to address not only production efficiency, but also societal and ethical challenges. In the Web of Science database, the earliest reference to this concept appears in Sachsenmeier (2016). In his work he mentions that bionics (the imitation or abstraction of nature's "inventions") and synthetic biology are revolutionary forces expected to impact industrial development. Next, in 2018, Özdemir and Hekim expanded the discourse in their review examine how extreme automation driven by the Internet of Things (IoT), artificial intelligence (AI) and Big Data analytics creates unprecedented opportunities as well as vulnerabilities. Complementing these technological perspectives, Kang (2018) provides a comparative analysis of national development strategies. By contrasting the approaches of Germany and Japan, Kang illustrates that the evolution towards Industry 5.0 is as much a matter of socio-political adaptation as it is of technological innovation. His analysis suggests that future industrial strategies must not only harness emerging technologies but also integrate socio-political and ethical considerations to remain relevant in a hyper-connected global landscape.

Xu et al. (2021), in their article, contend that Industry 5.0 represents a value-driven evolution that builds upon the technological advances of Industry 4.0 while integrating broader societal priorities. Since 2017 scattered academic efforts have gradually converged on the concept of the Fifth Industrial Revolution – a convergence that culminated in the European Commission's formal call in 2021. Drawing a parallel to the top-down approach of Industry 4.0 initiated by the German government in 2011, the authors emphasize that Industry 5.0 is not merely a continuation of previous technological progress but a systematic approach that places human-centricity, sustainability and resilience at its core.

In the discussion by Tallat et al. (2024) on Industry 5.0, the authors describe the paradigm as retaining the same fundamental parameters: human-centricity, sustainability and resilience; as previously outlined, while also marking a notable convergence of advanced technologies and human ingenuity. They explain that Industry 5.0 fuses the efficiency and precision of robotics with the unique cognitive and creative abilities of human professionals, thereby creating a manufacturing ecosystem where automated processes are harmoniously integrated with human decision-making. The authors further argue that such a synthesis not only improves industrial efficiency and facilitates mass personalization but also bridges the gap between the digital and physical realms, ultimately fostering a Social Smart Factory environment where collaborative robots

(cobots) work seamlessly alongside human operators. This unified approach ensures that the transformative potential of Industry 5.0 is directed towards creating a more resilient, innovative and human-centred industrial future.

Nexus of ESG and SDGs

Environmental, Social and Governance (ESG) represents a comprehensive framework that integrates ESG factors into the decision-making processes of companies and investors. In today's globally interconnected economy, these dimensions are essential not only for ensuring the sustainability of business operations but also for fostering stability and growth in financial markets.

The roots of ESG can be traced back to the CSR movement of the 1970s and 1980s, when scholars and practitioners began to question the narrow focus on profit maximization. Freeman's (1984) stakeholder theory argued that a firm's success depends on its ability to create value for a wide range of stakeholders rather than solely for its shareholders. In 1997 Elkington introduced the "triple bottom line" concept, which expanded corporate performance evaluation to include social and environmental dimensions alongside economic outcomes. In 2011, the notion of "creating shared value" further blurred the lines between profit and purpose, encouraging companies to integrate social and environmental goals into their core business strategies (Porter & Kramer, 2011).

In 2015, all United Nations Member States embraced the 2030 Agenda for Sustainable Development – a global framework aimed at securing peace, prosperity and a healthy planet. At the core of this agenda are the 17 Sustainable Development Goals (SDGs), which seek to reduce poverty, improve health and education, reduce inequalities and drive economic growth while addressing challenges such as climate change. This agenda is the result of decades of international collaboration. The journey began with the 1992 Earth Summit in Rio de Janeiro and its Agenda 21, which called for global partnerships in sustainable development. In 2000, the Millennium Declaration paved the way for the Millennium Development Goals (MDGs) to combat extreme poverty. The commitment to social and environmental progress was further strengthened by the Johannesburg Declaration in 2002. The 2012 Rio+20 conference further advanced these efforts by launching the process to develop a broader set of goals. In 2015, the United Nations General Assembly initiated negotiations on the post-2015 development framework, a process that ultimately led to the adoption of the 2030 Agenda for Sustainable Development containing the 17 SDGs at the UN Sustainable Development Summit (United Nations, n.d.a).

Both ESG and SDG frameworks share common principles, emphasizing responsible practices and positive impacts on the environment. Recognizing these shared goals encourages a unified exploration that can reveal deeper insights and foster long-term sustainable transformation.

The first Web of Science-indexed study connecting ESG and SDGs by Betti et al. (2018) established a clear link between ESG criteria and the United Nations' SDGs. This research dispelled the notion that sustainable practices compromise financial returns. By mapping 30 key ESG issues identified by the Sustainability Accounting Standards Board (SASB) to the SDGs, the study demonstrates that prioritizing material ESG factors can enhance both financial performance and sustainable development outcomes. ESG factors are increasingly integrated into portfolio strategies, and investors are drawn to options that are aligned with the SDGs. Naffa and Fain (2020) examined whether returns are compromised when ESG-aligned megatrend strategies are pursued, by analysing the risk-adjusted performance of global equity investments from 2015 to 2019. Nine themes were considered, including environmental (energy efficiency, food security, water scarcity), social (ageing, millennials, urbanization) and governance (cybersecurity, disruptive technologies, robotics) megatrends. Hieu and Hai (2023), in their article, state that the integration of ESG responsibilities with key economic factors has been found to positively impact the achievement of the Sustainable Development Goals in the BRICS countries. They demonstrated that higher ESG scores, economic growth, foreign direct investment, net national income, and inflation contributed positively to the SDG index, with both short-run and long-run effects being confirmed.

Overall, the evidence suggests that ESG-themed megatrend investing can contribute to achieving sustainable development goals without compromising financial returns. Moreover, while higher transaction costs might sometimes be incurred, they could either reflect an investor's readiness to accept a modest return trade-off in favour of sustainability or indicate the possibility of cost reductions in the future.

METHODOLOGY

This SLR was inspired by the approach of Baltazar et al. (2023). This review was guided by the following research questions:

RQ1: *What is the current state of research on Industry 5.0 in relation to ESG and SDGs?*

RQ2: *What thematic areas are most commonly explored in research linking Industry 5.0, ESG and SDG?*

TABLE 1. Article search parameters

Database	Web of Science
Date of search	January 10th 2025
Document types	Article
Languages	English
Publication years	NOT 2025
Search field	Topic (title, abstract, author keywords, and KeyWords Plus)
Query	((“Industry 5.0” OR “Fifth industrial revolution” OR “i5.0” OR “Industry 5”) AND (“ESG” OR (“environmental” AND “social” AND “governance”) OR “SDGs” OR “SDG” OR “sustainable goals” OR “sustainable development goals”))

SOURCE: Own elaboration, 2025

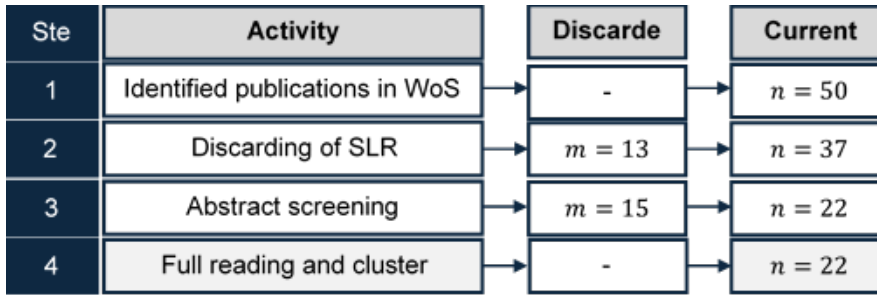

FIGURE 1. Article selection for SLR
SOURCE: Own elaboration, 2025

To answer these questions, a specific query was formulated and entered into the Web of Science (WoS) database to prevent duplication of records. The following query was designed to capture publications addressing topics related to Industry 5.0, ESG (Environmental, Social and Governance), and SDGs (Sustainable Development Goals). Full search parameters are shown in Table 1.

As a result of this search, an initial set of 50 publications was retrieved. In the second step, 13 systematic literature review papers were excluded to focus exclusively on original research and relevant studies, leaving 37 publications for abstract screening in the third step. This process assessed the relevance of the remaining studies and led to the exclusion of 15 additional publications, resulting in a final sample of 22 articles. In the fourth and final step, the full texts of these articles were read in detail and analysed using a keyword cluster analysis in VOSviewer (n.d.).

RESULTS

In this section descriptive analysis and content analysis (made by cluster analysis using VOSviewer) will be introduced.

Descriptive analysis of publications

Figure 2 presents both the annual number of publications and the corresponding total citations in the Web of Science (WoS) database from 2021 to 2024. In 2021, there was only one relevant publication, which had accumulated four citations to date. The following year, 2022, saw a modest rise to five relevant publications, accompanied by a substantial increase in citations (416). In 2023 the number of publications remained at five, although the total citations declined to 104. Notably, in 2024, there was a marked surge in publications (11), while the citation count (24) remained relatively low, likely reflecting the shorter timeframe available for citations to accumulate.

Figure 3 presents the partial distribution of pu-

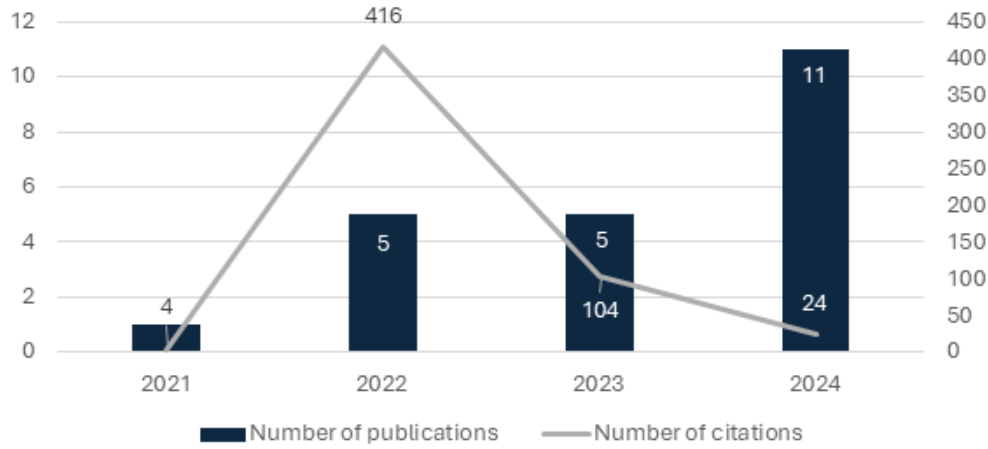

FIGURE 2. Number of publications and citations per year
SOURCE: Own elaboration, 2025

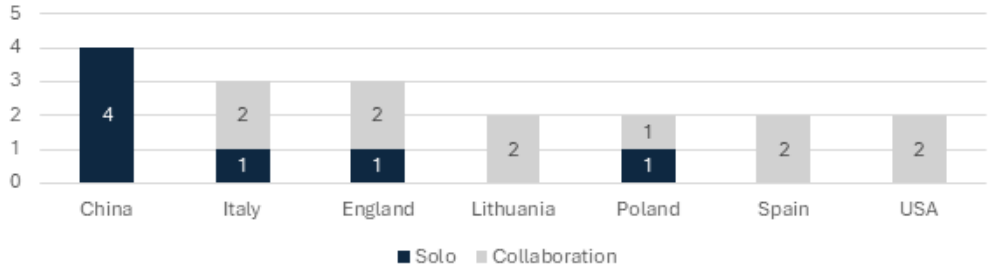

FIGURE 3. Number of publications per country
SOURCE: Own elaboration, 2025

blications per country, distinguishing between "Solo" (where all authors are from the same country) and collaborative works.

In our analysis, China stands out with the highest number of articles in solo as well in total articles. This domestic research focus mirrors the country's strong commitment to implementing the SDGs through national policies and initiatives (United Nations, n.d.b).

There are additional countries that are represented by only a single publication, whether solo-country-authored or collaborative. These countries are listed in Table 2.

Content analysis

Cluster analysis conducted in VOSviewer divided articles' content into distinct clusters, which were later analysed as groups.

In order to capture the overall thematic structure of the literature, the initial set of 50 publications was used to extract the data from the WoS to perform a bibliographic analysis in VOSviewer. During the analysis, the co-occurrence of keywords was examined and automatically divided into three primary thematic clusters, which were named based on their keyword profiles:

1. Management and Sustainability (green),
2. Technology and the Human Factor (red),
3. Digital Innovation and Future Technologies (blue).

This analysis was intended to provide an objective overview of the main topics emerging from the literature, ensuring that no potential thematic area was omitted.

Based on the article abstracts, the individual publications were assigned to the three identified clusters by comparing the content of each abstract with the defining keywords of each cluster. This categorization allowed for the organization of the articles into meaningful thematic groups, thereby facilitating a more

TABLE 2. List of countries with one publication

Type	Country
Solo	Albania, Colombia, Hungary, Mexico, Russia, Slovakia, Slovenia, Thailand
Collaboration	Bangladesh, Canada, Croatia, France, New Zealand, Portugal, Qatar, Sweden, United Arab Emirates

SOURCE: Own elaboration, 2025

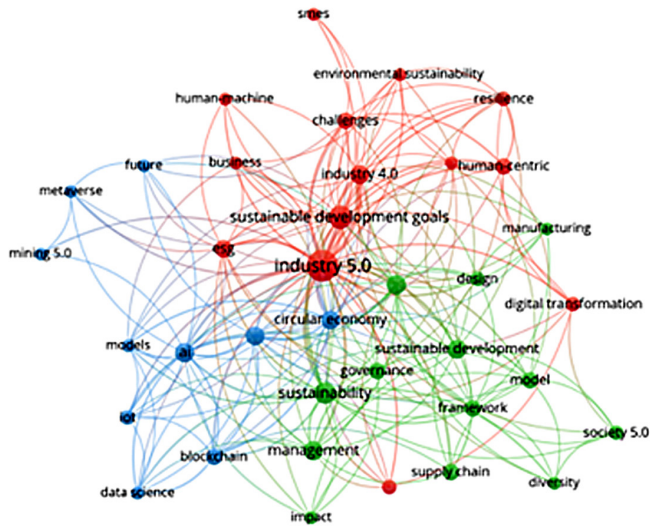

FIGURE 4. vOSviewer cluster map
SOURCE: Own elaboration, 2025

TABLE 3. cluster parameters

Cluster	Cluster name	Number of articles	Keywords
1	Management and Sustainability	10	design, diversity, framework, governance, impact, innovation, management, manufacturing, model, society 5.0, supply chain, sustainability, sustainable development
2	Technology and the Human Factor	6	challenges, digital transformation, environmental sustainability, ESG, human-centric, human-machine, industry 4.0, industry 5.0, resilience, SMEs, business, social sustainability, sustainable development goals, systems
3	Digital Innovation and Future Technologies	6	AI, blockchain, circular economy, data science, future, IoT, metaverse, mining 5.0, models, technology

SOURCE: Own elaboration, 2025

TABLE 4. Publications' characteristics (part 1/3)

Cluster	Citation	Methodological approach	Source of data	Sample	Method
Management and Sustainability	(Chen et al., 2024a)	Quantitative	Database (CNRDS, CSMAR, WIND)	1140 supplier-customer pairs (528 suppliers, 408 customers)	Panel regression, OP, LP, 2SLS, GMM
	(Zhang, 2024)	Quantitative Survey	Questionnaire	749 responses, agricultural industry stakeholders	SEM
	(Chen et al., 2024b)	Quasinatural Experiment	Database (CSMAR, WIND)	27 338 observations from Chinese A-share companies (2010-2020)	DID regression, PSM, 2SLS, GMM analysis
	(Ceko et al., 2024)	Quantitative Regression Analysis	Secondary Data: UNSDG Report 2023 & GII Report 2023	131 countries	Correlation, inferential regression analysis
	(Babkin et al., 2023)	Case Study with Quantitative Framework Development	Internal ESG databook and corporate reports of NLMK Group	NLMK Group industrial ecosystem in Russia (2016–2020)	Indicator normalization, sub-index and integral index computation, comparative data analysis
	(Asif et al., 2023)	Conceptual/ Theoretical Analysis	Secondary Data & Literature Review	N/A	Conceptual framework
	(Hao et al., 2022)	Grounded Theory + Quantitative Multi-criteria Analysis	Chinese coal enterprises (evaluated via ESG indicators)	31 ESG disclosure documents; expert panel (11 members)	Grounded theory coding, Entropy Weight Method, Cloud Model, ISM/ MICMAC analysis, Nominal Group Technique
	(Ghobakhloo et al., 2022)	Conceptual / Theoretical Analysis	Secondary Data, Literature Review	31 eligible documents; 11 expert panel members	Content-centric synthesis, Interpretive Structural Modelling (ISM), MICMAC analysis, Nominal Group Technique

SOURCE: Own elaboration, 2025

TABLE 4. Publications' characteristics (part 2/3)

Cluster	Citation	Methodological approach	Source of data	Sample	Method
	(Richnák & Fidlerová, 2022)	Quantitative Survey	Questionnaire, Secondary Data	105 manufacturing enterprises in Slovakia	Questionnaire survey, Descriptive statistics, Inferential statistics
	(Wiśniewska-Sałek, 2021)	Quantitative Statistical Analysis	Secondary data (Central Statistical Office, State Forests, REGON database)	Data on the furniture industry in Poland (acquisition, sales)	Descriptive statistics, correlation analysis, regression modelling
Technology and the Human Factor	(Rojas et al., 2024)	Experimental Prototype Development, Usability Evaluation	Data from Prototype Testing, User Questionnaire	5 university students (operators in training)	VR environment design
	(Ojstersek, Javernik & Buchmeister, 2024)	Simulation-based evaluation, ESG framework integration	Real-world production process data (machine costs, energy consumption, worker costs)	One factory production line with 7 CNC machines + 1 assembly workplace (manual vs. human-robot collaborative setup)	Discrete-event simulation in *Simio*, comparing manual assembly vs. HRC workstation, with ESG metrics (economic, environmental, social, governance)
	(Madhavan et al., 2024)	Quantitative Survey; Proposal of Model	Self-administered questionnaire and official SME registry data	42 seafood processing SMEs in Thailand (16 owners, 30 top-level managers)	Quantitative self-assessment using a 6-level readiness scale across 7 factors (percentage analysis)

SOURCE: Own elaboration,

structured analysis of the literature.

Cluster 1: Management and Sustainability (n = 10)

This cluster is represented by ten articles in our analysis and focuses on sustainability management, Environmental, Social, and Governance (ESG) principles, and Sustainable Development Goals (SDGs) in business. It emphasizes the implementation of sustainable practices in manufacturing, supply chains, and logistics.

Wiśniewska-Sałek (2021) conducted a study on sustainable supply chain management in the Polish furniture industry. Based on data concerning wood acquisition, wood sales, and production dynamics, and using statistical methods, the study concluded that while significant production potential was demonstrated and the use of natural resources was increasing, instability in production dynamics was also observed. The integration of SDG activities was portrayed as a fundamental driver in shaping sustainable practices across the supply chain by linking environmental management directly to the pursuit of SDG targets.

Richnák and Fidlerová (2022) examined the impact and potential of SDGs in the context of Industry 4.0/5.0 within industrial enterprises. Data from 105 manufacturing enterprises were analysed and the implementation of SDGs was evaluated. The study found that over 82 % of enterprises had adopted SDGs, with the highest levels of implementation observed in the

TABLE 4. Publications' characteristics (part 3/3)

Cluster	Citation	Methodological approach	Source of data	Sample	Method
	(Mladineo et al., 2024)	Quantitative survey	Self-reported responses, online questionnaire	63 manufacturing enterprises in Croatia	Quantitative analysis, descriptive statistics
	(Carayannis & Morawska-Jancelewicz, 2022)	Conceptual / Theoretical paper; policy-oriented analysis	Literature review, policy documents	N/A	Conceptual framework building; application of Quadruple/ Quintuple Helix Model
	(Sindhwani et al., 2022)	Quantitative, Proposal of Model	Questionnaire (Expert Opinions)	9 experts	Pythagorean Fuzzy Delphi, PF-AHP, PF-Co-CoSo
Digital Innovation and Future Technologies	(Al Amin & Baldacci, 2024)	Quantitative Case Study	Questionnaire, Expert Opinions	15 experts in focus group discussions, 22 survey responses from Bangladeshi RMG industry professionals	Interpretive Structural Modelling (ISM), fuzzy DEMATEL
	(Shafique et al., 2024)	Quantitative survey	Questionnaire	179 respondents	Partial Least Squares Structural Equation Modelling
	(Fernández Miguel et al., 2024)	Case study/ experimental demonstration	Laboratory tests, cost analysis of the AdM process	A customized PlayStation 4 trigger used as a case study	Digital reverse engineering
	(De Giovanni, 2023)	Qualitative conceptual analysis	Secondary data, SLR	N/A	Triple Bottom Line
	(Redchuk et al., 2023)	Case study	18 months of IIoT-generated process and ambient data	1 North American food ingredient company	Low-Code AI platform with prebuilt ML templates
	(Serrano, 2023)	Proposal of Model	Document analysis	N/A	Conceptual model development

SOURCE: Own elaboration,

mechanical engineering and automotive industries. Significant relationships were identified between environmental management influenced by SDGs and sustainable practices in production and logistics, while green manufacturing and logistics were found to be significantly associated with selected Industry 4.0 technologies.

Ghobakhloo et al. (2022) developed a strategy roadmap for Industry 5.0 contributions to SDG values. A reference model of Industry 5.0 was constructed, and its sustainable development functions were identified through a content-centric synthesis of the literature and interpretive structural modelling. The study found that sustainability values are delivered by functions such as circular intelligent products, employee technical assistance, intelligent automation, open sustainable innovation, renewable integration, and supply chain adaptability. It was recommended that these functi-

ons be developed sequentially to maximize synergistic sustainability gains, and a roadmap was provided to guide Industry 5.0-driven sustainable transformation.

Hao et. al. (2022) examined the performance of coal enterprises from an ESG perspective. A framework was constructed by combining grounded theory, the entropy method, and the cloud model. The FESG structural dimension model was derived from ESG and triple bottom line theories, thereby integrating financial, environmental, social, and governance performance. The model was applied to a case study that demonstrated its ability to provide an objective, comprehensive, and scientifically valid measure of sustainable development performance in coal enterprises.

Asif et al. (2023) argued that current ESG reporting is limited by retrospective data and a lack of customization, scope, and cost-efficiency, and that these shortcomings can be addressed by integrating technologies such as blockchain, digital twins, AI, and IoT. The proposed framework was validated by demonstrating how these technologies can be applied for improved authenticity, real-time reporting, extended supply chain coverage and reduced disclosure costs.

Babkin et al. (2023) focused on the development of a framework for assessing circular maturity in industrial ecosystems. A set of indicators was defined and distributed across three driver projections (circular potential, circular activity, and circular efficiency) and the framework was validated using data from the NLMK Group (2016 – 2020). The results showed that circular maturity increased until 2018 and subsequently declined due to reduced environmental audits and external economic challenges.

Ceko et al. (2024) analysed the relationship between Innovation Index and SDG Index. The authors argued that sustainable development is essential for societal progress and an improved quality of life. They concluded that innovation, as embodied in the ISO 56000 family of standards, should be adopted as an efficient tool by all stakeholders to achieve and sustain sustainable development scenarios.

Chen et al. (2024a) found that customers' green technological innovation (GTI) positively affects suppliers' total factor productivity (TFP), and this relationship is strengthened by suppliers' long-term orientation, measured through ESG performance and R&D investment. However, non-substantial GTI was found to weaken the positive impact of R&D on TFP. These spillover effects were particularly strong in state-owned, high-tech and non-polluting enterprises.

Zhang (2024) examined how Agriculture 5.0 and Industry 5.0 contribute to sustainable development using stakeholder theory. The study demonstrated that Agriculture 5.0 (by optimizing resource use, enhancing food security, and reducing waste through precision farming) positively influences sustainable development. Likewise, Industry 5.0 improves industrial processes through automation and data-driven decision-making, thereby enhancing sustainability. Moreover, environmental policies were shown to significantly moderate these relationships, strengthening the positive impacts on SDG dimensions.

Chen et al. (2024b) investigated the effect of digital transformation on ESG performance in Chinese A-share listed companies, using panel data from 2010 to 2020. The study found that the implementation of China's Environmental Protection Law (EPL) significantly enhances ESG performance among resource- and environment-oriented enterprises, while digital transformation itself is positively associated with improved ESG performance. Robustness tests (including 2SLS and GMM) further confirmed these results.

The reviewed literature in this cluster underscores the critical role of strategic management in integrating technological innovation with sustainability frameworks. Companies are increasingly recognizing that digital transformation and the adoption of Industry 5.0 principles are not merely technical upgrades but strategic imperatives that drive competitive advantage. In this context, strong ESG performance is pivotal – it not only reflects a company's commitment to responsible practices but also reinforces long-term stakeholder trust and market resilience. For instance, robust ESG metrics have been shown to amplify the positive effects of green technological innovation on productivity, suggesting that firms with a strategic focus on environmental, social and governance factors are better positioned to leverage technological advancements. Similarly, aligning corporate strategies with SDGs has emerged as a best practice. Integrating SDG principles into business models promotes sustainable production, environmental stewardship, and operational efficiency – all key elements that modern managers consider when planning for long-term growth. Overall, these insights indicate that a holistic strategy (merging advanced digital technologies, ESG performance and SDG alignment) is essential for firms aiming to achieve sustainable competitive advantage and robust operational performance in today's dynamic business environment.

Cluster 2: Technology and the Human Factor (n = 6)

The articles in this cluster (n = 6) focus on technological and social innovation with an emphasis on human needs and the circular economy. This cluster represents the transition toward more sustainable production and management processes, with a strong focus on social impact.

Carayannis and Morawska-Jancelewicz (2022) argue that the human-centric approach in Industry

5.0 aims to enhance production processes – not by replacing humans but by complementing their skills with smart machines to achieve greater customization, satisfaction, and resilience. In practice, this means that organizations, including universities, are encouraged to redesign their systems and curricula to foster interdisciplinary learning and ethical innovation. The study showed that the integration of Industry 5.0 principles with human-centric innovation not only transforms production and service delivery but also ensures that technological progress directly benefits society by improving quality of life and promoting sustainable practices.

In their article, Sindhwani et al. (2022) proposed a decision framework using Pythagorean fuzzy methods to identify and rank key enablers for Industry 5.0. The study found that personalized production and collaborative technologies (such as bionics and IoT systems) are critical for building resilient, innovative industrial systems. Sustainability and social values were emphasized in ways that align with several SDGs. Based on these results, the authors recommend investing in technologies that integrate human skills with advanced digital solutions, ultimately fostering both operational resilience and improved social value.

Mladineo et al. (2024) assessed the Croatian manufacturing industry's maturity in adopting advanced digital technologies (Industry 4.0) and evaluated its progress toward human-centric goals of Industry 5.0. Using an online survey and a tailored maturity model, the study found that the average maturity level is 2.45 – indicating that most companies are still at early stages (mainly Industry 2.0 to 3.0). Although a few enterprises have begun integrating modern automation and digital tools, progress in human-centricity remains low, as evidenced by limited employee training and engagement. The authors recommend targeted state and EU funding to accelerate technology adoption and improve organizational practices such as lean management and workforce development.

Interestingly, Madhavan et al. (2024) bridge technology and human-centricity by evaluating seafood SMEs' readiness for Industry 5.0. Their study assessed both advanced digital technologies (such as automation, robotics, AI, and integrated ERP/IoT systems) and human-centric management practices, including effective business process documentation, communication, and lean management. The study found that while these SMEs predominantly use older technologies (Industries 1.0 – 3.0), they are relatively more advanced in their human-centric processes.

Ojstersek et al. (2024) proposed a simulation-based framework for evaluating collaborative manufacturing systems using ESG criteria in an Industry 5.0 setting. The framework compares traditional manual assembly with a human-robot collaborative (HRC) workstation by incorporating real-world data into simulation models. The study found that HRC improves production efficiency by increasing finished products, reducing scrap rates (from 8 % to 4.5 %), lowering idle and processing costs and achieving better machine utilization. Although HRC systems require slightly higher energy due to the integration of collaborative robots, the overall benefits (such as reduced labour costs and improved worker well-being) support a more sustainable and human-centric production approach. The authors recommend further enhancing HRC systems by refining energy management and cost efficiency, while also integrating worker stress monitoring through wearable technologies.

Rojas et al. (2024) presented a smart interface that integrates haptic gloves with virtual reality for industrial operator training. Using a human-centric, 5S approach (Social, Sustainable, Sensing, Smart and Safe), the system demonstrated improved training outcomes, reduced real-world errors, and high user satisfaction. The system was found to support sustainable industrial practices, contributing to the attainment of SDG 8 by enhancing worker well-being and SDG 9 by fostering innovative and efficient production processes.

This collection of studies highlights a clear trend toward merging advanced technologies with human-centric approaches to enhance industrial practices and training. Collectively, the research underscores the importance of complementing digital tools with human skills to boost efficiency, safety, and sustainability. It further recommends enhancing feedback realism in training systems through AI integration, refining energy management and cost efficiency in collaborative manufacturing and promoting interdisciplinary learning and ethical innovation. These recommendations aim to create adaptive, sustainable, and socially responsible industrial processes that effectively combine human skills with digital advancements.

Cluster 3: Digital Innovation and Future Technologies (n = 6)

This cluster, comprising 6 articles, maps the role of digital transformation and modern technologies in shaping Industry 5.0. It explores future technological trends such as the IoT, AI and blockchain, which drive innovation and advancements across various sectors.

Serrano (2023) explored how digital technologies (AI, IoT, 5G) enhance the functionality and sustainability of built assets and infrastructure. It introduces an omni-management model that decomposes asset operations into atomic micro-services covering user interactions, spatial design, management, and technology. The findings suggest that standardizing

assets through digital integration and decentralized frameworks (including tokenization) can improve operational efficiency, reduce costs, and support ESG and Net Zero targets.

Redchuk et al. (2023) present a case study from a North American food ingredient company that adopted an IIoT-enabled, low-code AI platform to optimize energy consumption in its process manufacturing operations under the Industry 5.0 model. As a result, the company achieved a 2.5% improvement in thermal efficiency and a 4% reduction in fuel costs, which also contributed to lowering its greenhouse gas emissions. The authors recommend that traditional industries enhance their OT/IT integration and focus on empowering internal process experts to drive AI adoption. Overall, the approach not only boosts operational efficiency and cost savings but also supports environmental sustainability, aligning with key ESG principles and the UN SDGs.

De Giovanni (2023) focused on the sustainability of metaverse technologies as a pathway toward Industry 5.0. Metaverse's economic, environmental, and social impacts are evaluated by applying a triple bottom line analysis, an ESG framework, and linking the technology to the UN SDGs. The study found that the metaverse offers promising opportunities (such as new digital markets, enhanced resource efficiency and innovative customer experiences) but also presents significant challenges. High energy consumption, environmental footprints from blockchain and data centres, potential job displacements, and social inequalities are key concerns.

Fernández-Miguel et al. (2024) examined Additive Digital Molding (AdM) as an Industry 5.0 solution to enhance supply chain agility and sustainability. Combining digital reverse engineering, 3D printing and injection molding, AdM enables cost-effective customization, rapid prototyping and decentralized models like direct and home manufacturing. The results highlighted reduced costs, greater flexibility, and resilience against disruptions. The study aligns AdM with SDGs on clean energy, sustainable industry, climate action, and decent work, emphasizing its role in creating human-centric and sustainable supply chains.

Shafique et al. (2024) focused their research on key Industry 5.0 technologies (AI, Big Data, IoT, ML and blockchain) and their role in promoting eco-design, management systems, and investment recovery as components of circular economy. For this study, data from 179 industry respondents were collected and analysed using SEM, which revealed that Industry 5.0 capabilities directly improve sustainable performance (measured across economic, environmental, and social dimensions). Moreover, circular economy practices serve both as a mediator and a moderator in this relationship, indicating that effective circular strategies further amplify the positive impact of technological advancements on sustainability and SDGs.

Al Amin and Baldacci (2024) examined the integration of blockchain technology and Industry 5.0 in the Bangladeshi Ready-Made Garments industry to enhance sustainability. Using ISM and fuzzy DEMATEL methods, the research identified 14 critical synergies and categorized them into dependent, independent and linkage factors. Key findings highlight reverse logistics and recycling, supply chain collaboration and visibility, and ethical and fair-trade practices as the most influential synergies driving sustainability. Real-time environmental monitoring and emission tracking were found to be essential for compliance and reducing environmental impact, while automated compliance and reporting improve efficiency. The study recommends prioritizing blockchain-based traceability systems, digital twin technology and decentralized renewable energy platforms to strengthen sustainability efforts. These findings align with SDGs, emphasizing responsible production, clean energy, and ethical labour practices.

The body of this cluster emphasizes that integrating advanced digital technologies with sustainable practices can significantly transform industrial processes. The findings reveal that leveraging blockchain, AI, IoT, Big Data, and other related Industry 5.0 technologies enhances sustainability by improving traceability, streamlining supply chain collaboration, and optimizing resource use. Overall, these studies recommend increased investment in Industry 5.0 technologies, the development of supportive regulatory frameworks, and the implementation of targeted training programs. Such measures aim to enhance circular economy strategies, promote ethical and responsible practices, and ultimately drive sustainable performance in line with broader ESG goals.

DISCUSSION

This study systematically reviewed the literature related to the intersection of ESG (Environmental, Social and Governance) and SDGs (Sustainable Development Goals) with the context of Industry 5.0. The discussion is divided into two main parts. The first part presents insights related to the research questions, while the second part summarises the main findings from the literature, highlights existing research gaps and challenges, and outlines implications for future research.

Addressing research questions

RQ1: *What is the current state of research on Industry 5.0 in relation to ESG and SDGs?*

The current state of research on Industry 5.0 in relation to ESG and SDGs reveals a growing interest in integrating sustainable business practices with technological advancements. The literature emphasizes that Industry 5.0 fosters sustainability by promoting responsible production, circular economy principles, and human-centric digital transformation. However, studies vary in their emphasis on either ESG, SDGs or both. The growing number of publications in this field reflects increasing academic and industrial interest - from one paper in 2021 to eleven papers in 2024. This trend highlights the expanding relevance of Industry 5.0 in sustainability discussions. Moreover, research in this area benefits significantly from international collaboration, as indicated by the diversity of co-authorship across multiple countries. For further analysis, the reviewed papers are categorized into three groups: those addressing Industry 5.0 and SDGs, those focusing on Industry 5.0 and ESG, and those covering Industry 5.0 in relation to both SDGs and ESG.

Several studies focused solely on the connection between Industry 5.0 and SDGs emphasizing how sustainable practices contribute to global development goals. Wiśniewska-Sałek (2021) and Richnák and Fidlerová (2022) examined sustainable supply chain management and the role of SDGs in business practices, showing how SDG-aligned strategies enhance environmental management and logistics. Ghobakhloo et al. (2022) developed a strategy roadmap for aligning Industry 5.0 contributions with SDGs, particularly through circular intelligent products and sustainable innovation. Carayannis and Morawska-Jancelewicz (2022) and Sindhwani et al. (2022) explored the role of human-centric production approaches and collaborative technologies in Industry 5.0, showing how they align with SDG targets such as responsible consumption and economic growth. Madhavan et al. (2024) and Rojas et al. (2024) examined Industry 5.0's contribution to industrial training and workforce transformation, demonstrating its role in achieving SDG-related labour and education improvements. Ceko et al. (2024) and Zhang (2024) analysed how Industry 5.0 enhances circular economy practices, optimizing resource use and improving sustainable production. Al Amin and Baldacci (2024) and Shafique et al. (2024) investigated the role of blockchain and AI in supporting SDGs, particularly in the context of ethical supply chain and transparency. Fernández-Miguel et al. (2024) explored the adoption of advanced digital manufacturing techniques and cognitive digital twins, emphasizing their potential to enhance sustainable production and industrial resilience. These studies collectively illustrate that Industry 5.0 plays a significant role in advancing SDGs through sustainable supply chain management, technological innovation and digital transformation.

Research on ESG within Industry 5.0 explores its impact on corporate sustainability, governance and responsible investment. Hao et al. (2022) developed a framework for evaluating coal enterprises' ESG performance, integrating financial, environmental and governance metrics. Asif et al. (2023) examined how blockchain and AI technologies can improve ESG reporting, enhancing transparency and efficiency in corporate sustainability disclosures. Babkin et al. (2023) introduced a framework for assessing circular maturity in industrial ecosystems, demonstrating how Industry 5.0 enhances resource efficiency and ESG-aligned sustainable management. Ojstersek et al. (2024) proposed a human-robot collaborative system that optimizes ESG-compliant manufacturing, balancing efficiency and sustainability in industrial production. Chen et al. (2024a, 2024b) analysed how ESG performance influences digital transformation, showing that robust ESG strategies drive long-term industrial resilience and technological adaptation. Serrano (2023) explored how AI, IoT and 5G can enhance infrastructure sustainability, aligning digital transformation with ESG compliance and corporate responsibility. These studies indicate that Industry 5.0 contributes to ESG goals through improved reporting, sustainable resource management and digital transformation strategies.

Two studies integrated both ESG and SDGs. De Giovanni (2023) examined the metaverse's sustainability implications, emphasizing responsible digitalization strategies. Rojas et al. (2024) explored human-centric industrial training, demonstrating its alignment with ESG governance and SDGs.

RQ2: *What thematic areas are most commonly explored in research linking Industry 5.0, ESG and SDG?*

Our research is organised into three major thematic clusters: Management and Sustainability, Technology and the Human Factor and Digital Innovation and Future Technologies. These clusters reflect the evolving intersection of digital transformation, sustainability, and human-centric industrial advancements. Each cluster addresses several key topics that are either specific to that cluster or overlap with others, demonstrating the interconnected nature of these research areas. The structure of these clusters and their thematic intersections are illustrated in Figure 5.

The Management and Sustainability cluster focuses on integrating ESG principles and SDGs into

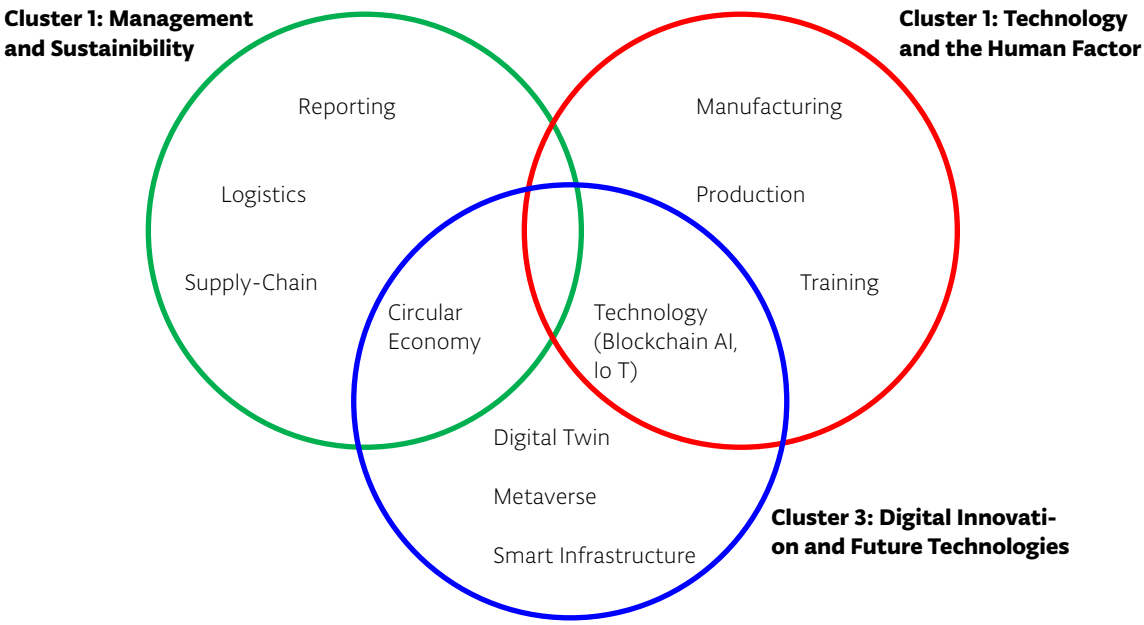

FIGURE 5. Thematic areas
SOURCE: Own elaboration, 2025

business and industrial strategies. Key themes include sustainable supply chain management, green logistics, ESG reporting, and circular economy practices, which overlap with the Digital Innovation and Future Technologies cluster.

The Technology and the Human Factor cluster explores the role of technological advancements in enhancing human skills and industrial efficiency. It covers themes such as manufacturing, production, training, and emerging technologies (such as blockchain, AI and IoT), which overlap with the third cluster.

The Digital Innovation and Future Technologies cluster includes, in addition to the previously mentioned themes of circular economy and technology, topics such as digital twins, the metaverse and smart infrastructure.

These clusters are strongly interconnected, as sustainability management increasingly relies on digital innovations and human-centric approaches are enhanced by emerging technologies. Future research is expected to focus on advanced ESG reporting, as AI and blockchain will likely play key roles in improving real-time monitoring, transparency, and accountability; human-machine collaboration, which will explore optimal frameworks for integrating automation with human-centric processes to enhance efficiency and inclusivity; and the role of governmental and international policies in shaping sustainable industrial practices and digital innovation strategies. Additionally, future research on technology, particularly the rapid expansion on digital twins, metaverse applications and decentralized technologies, will assess their implications for ESG and SDGs. Finally, more publications are expected to explore how immersive digital tools (such as VR, AR and AI-driven learning platforms) can enhance workforce training, upskilling and adaptability in Industry 5.0 environments.

CONCLUSION

This study highlights the increasing relevance of Industry 5.0 as a key driver of sustainable development. The reviewed literature is organised into three thematic clusters: (1) Management and Sustainability, (2) Technology and the Human Factor, and (3) Digital Innovation and Future Technologies.

The findings emphasize that Industry 5.0 has a significant impact on ESG (Environmental, Social and Governance) and SDG-related (Sustainable Development Goals) efforts through digital innovation, human-centric technologies, and strategic sustainability management. However, inconsistencies in definitions and measurement frameworks persist in the literature, particularly when evaluating the effectiveness of Industry 5.0's contribution to ESG and SDGs performan-

ce. The integration of Industry 5.0 with ESG and SDGs strategies remains fragmented, as different studies approach the topic from various perspectives, leading to a lack of standardized methodologies.

Future research should focus on developing comprehensive frameworks that systematically incorporate Industry 5.0 principles into ESG and SDG evaluations. To empirically validate the conceptual insights identified in this review, future studies should also prioritize sector-specific contexts such as automotive, mechanical engineering, energy, agriculture and supply chain management. These industries are particularly relevant due to their rapid digital transformation and strong links to sustainability challenges. Methodologically, longitudinal case studies could capture the dynamics of Industry 5.0 adoption and its effects on ESG and SDGs performance over time. Panel-data approaches may evaluate casual impacts of regulatory changes and digital transformation strategies, while field and quasi-experiments could enable direct testing of interventions such as human-robot collaboration or VR-based training systems. Mixed-methods research combining blockchain or IoT data with advanced modelling techniques could shed light on configurations that drive circular economy practices. Simulation-based evaluations, complemented by stress or well-being indicators, could further clarify the human-centric dimensions of Industry 5.0. Together, these approaches would provide a robust empirical foundation to inform both managerial practice and policymaking beyond speculative implications.

From a practical perspective, the findings carry important implications. Policymakers can leverage insights from Industry 5.0 research to design harmonized regulatory frameworks that balance technological innovation with sustainability objectives and ethical safeguards. At the same time, business leaders can apply Industry 5.0 principles to strengthen ESG reporting, enhance supply chain transparency, and foster workforce adaptability, which not only supports compliance but also creates long-term competitive advantage.

The main limitation of this study lies in the reliance on a single database (WoS), which may have led to the omission of relevant studies indexed elsewhere. Some high-quality studies may also have been excluded due to the applied screening criteria, and the diversity of methodologies across the literature further complicates direct comparisons.

Overall, this study underscores the critical role of Industry 5.0 in advancing sustainable development. While existing research highlights its potential to enhance ESG- and SDG-related initiatives, challenges remain in measurement, implementation, and policy alignment. Addressing these issues through future research and practical applications will be essential to fully harness the transformative power of Industry 5.0 within the global sustainability landscape.

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INDUSTRIJA 5.0 I NJEZINA ULOGA U UNAPRJEĐIVANJU NAČELA ESG-A I CILJEVA ODRŽIVOG RAZVOJA: SUSTAVNI PREGLED LITERATURE

SAŽETAK

Iako Industrija 4.0 nudi široko rasprostranjenu automatizaciju u raznim tehnologijama, ostaje pitanje je li industrijska evolucija završila. Posljednjih godina, pojam Industrija 5.0 koristi se za predstavljanje održivih industrijskih praksi usmjerenih na čovjeka, koje su usklađene s postizanjem načela zaštite okoliša, društva i upravljanja (ESG) koje su definirali Ujedinjeni narodi (UN). Ta načela služe kao okvir putem kojeg tvrtke mogu doprinijeti ispunjavanju globalnih Ciljeva održivog razvoja (SDG) UN-a. S obzirom na rastući značaj Industrije 5.0 u kontekstu održivosti, ova studija nastoji istražiti dva ključna istraživačka pitanja: (1) „Kakvo je trenutno stanje istraživanja Industrije 5.0 u odnosu na ESG i SDG?" i (2) „Koja se tematska područja najčešće istražuju u istraživanjima koja povezuju Industriju 5.0, ESG i SDG?". Kako bi se odgovorilo na ova pitanja, proveden je sustavni pregled literature, analizirajući konačni izbor od 22 rada. Identificirane su tri glavne skupine, kategorizirajući studije na sljedeći način: (1) Upravljanje i održivost, koja ispituje prakse upravljanja održivošću i ulogu ESG čimbenika u poslovanju; (2) Tehnologija i ljudski faktor, s naglaskom na presjeku tehnoloških i društvenih inovacija; i (3) Digitalne inovacije i buduće tehnologije, koje obuhvaćaju nove tehnološke trendove poput blockchaina, umjetne inteligencije (AI), Interneta stvari (IoT) i metaverzuma. Ova studija naglašava važnost strateškog planiranja, integracije kružnog gospodarstva i digitalne transformacije u poticanju održivosti. Iako se istraživanje Industrije 5.0 još uvijek razvija, ova studija pruža uvid u presjek automatizacije, usmjerenosti na čovjeka i ekološke odgovornosti.

KLJUČNE RIJEČI: *Industrija 5.0, ESG, ciljevi održivog razvoja (SDG)*