ENHANCING SUSTAINABILITY AND HUMAN CENTRICITY THROUGH EMERGING TECHNOLOGIES FROM INDUSTRY 4.0 TO INDUSTRY 5.0: AN INTEGRATIVE LITERATURE REVIEW

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OPEN ACCESS

How to cite this paper: Thompson-Bahm, H., Teixeira, J. E., & Lobo, R. C. G. (2025). Enhancing sustainability and human centricity through emerging technologies from Industry 4.0 to Industry 5.0: An integrative literature review. *Corporate Governance and Sustainability Review, 9*(3), 90–104. https://doi.org/10.22495/cgsrv9i3p7

ISSN Online: 2519-898X
ISSN Print: 2519-8971

Received: 27.01.2025
Revised: 28.04.2025; 17.06.2025
Accepted: 14.07.2025

JEL Classification: D78, J24, M11, O14, O33
DOI: 10.22495/cgsrv9i3p7

Abstract

In the early 2020s, the European Commission introduced the concept of "Industry 5.0", expanding upon the framework of Industry 4.0 by emphasizing integrating emerging technologies with sustainable, human-centered industrial processes. This paper explores the shift from Industry 4.0 to Industry 5.0, emphasizing artificial intelligence (AI), blockchain, and the Internet of Things' (IoT) role in enhancing sustainability and human well-being. While Industry 4.0 prioritizes automation and hyperconnectivity, Industry 5.0 prioritizes collaboration between humans and intelligent machines, balancing operational efficiency with eco-friendliness, redefining industrial paradigms with a focus on human-centric, sustainable outcomes and hyperconnectivity (Ivanov, 2023). Within this context, our research question is to what extent new technologies influence sustainability and human-machine collaboration in the transition from Industry 4.0 to Industry 5.0. To answer this question, we developed an integrative literature review (ILR) and bibliometric analysis to study the contribution of key technologies to environmental and social sustainability. The findings reveal how businesses adopting Industry 5.0 principles, centered on human-centric innovation and resilience, can lead the charge toward adaptable and sustainable industrial ecosystems. Industry 5.0 brings change that addresses critical environmental issues on a large scale (Ghobakhloo, Iranmanesh, Foroughi, et al., 2023). This research underscores the importance of aligning production methods with environmental and societal goals, offering a strategic roadmap for creating a more inclusive, sustainable, and human-focused industrial future.

Keywords: Sustainability, Human Centricity, Emerging Technologies, Industry 4.0, Industry 5.0

Authors' individual contribution: Conceptualization — H.T.-B.; Methodology — H.T.-B., J.E.T., and R.C.G.L.; Software — J.E.T.; Validation — H.T.-B., J.E.T., and R.C.G.L.; Formal Analysis — H.T.-B., J.E.T., and R.C.G.L.; Investigation — H.T.-B., J.E.T., and R.C.G.L.; Resources — H.T.-B., J.E.T., and R.C.G.L.; Data Curation — H.T.-B., J.E.T., and R.C.G.L.; Writing — H.T.-B., J.E.T., and R.C.G.L.; Visualization — H.T.-B., J.E.T., and R.C.G.L.; Supervision — J.E.T.; Project Administration — J.E.T.

Declaration of conflicting interests: The Authors declare that there is no conflict of interest.

Acknowledgements: The Authors acknowledge the valuable support of the Department of Business Administration, College of Business, Montana State University Billings, USA, and the Department of Economics, UNICENTRO, Brazil, to the development of this project.

1. INTRODUCTION

The industry landscape has been transformed by successive revolutions, which have revolutionized technology and manufacturing. Mechanization was introduced with the First Industrial Revolution, electricity and mass manufacturing with the Second (Akundi et al., 2022), and automation and information technology (IT) during the Third (Xu et al., 2021). Industry 4.0 introduced intelligent manufacturing, integrating cyber-physical systems, artificial intelligence (AI), Internet of Things (IoT), and big data to execute operations and productivity (Grybauskas et al., 2022). But it also created concern over the devastation of the environment and the loss of work. Industry 5.0 subsequently emerged, introducing high-tech technologies with human values and sustainability (Ghobakhloo et al., 2024; Laddha & Agrawal, 2024).

While Industry 4.0 emphasizes automation and efficiency, Industry 5.0 emphasizes resilience, ethical business, and human-machine collaboration (Corallo et al., 2024). IoT, AI, and cognitive digital twin (CDT) technologies enable real-time monitoring, predictive maintenance, and resource management optimization (Yadav et al., 2020; Mesjasz-Lech et al., 2024). This change aligns with carbon reduction and circular economy theory (Eriksson et al., 2024; Marcon et al., 2022). Human-centeredness is central, focusing on the well-being, safety, and belonging of employees through technologies like collaborative robots (Ivanov, 2023). Workforce training is also central to tackling talent retention and reskilling, being fundamental drivers of organizational performance (Enang et al., 2023). Leadership frameworks also need to shift to drive these changes effectively (Hussain et al., 2023).

The COVID-19 pandemic further highlighted the necessity for flexibility, compelling Industry 5.0 to embrace flexible, AI-based systems for long-term sustainability (Daniels et al., 2022). This revolution prioritizes cooperation among policymakers, companies, and stakeholders to promote sustainable innovation (Troisi et al., 2024). However, the literature indicates a gap: although the alignment of Industry 5.0 with the United Nations (UN) Sustainable Development Goals (SDGs) is widely debated, systematic frameworks are underdeveloped.

In response to the evolving landscape of industrial advancements, our study employs an integrative literature review and bibliometric analysis to investigate the impact of emerging technologies on sustainability and human-machine collaboration. The central research question guiding this inquiry is:

RQ: To what extent do new technologies influence sustainability and human-machine collaboration in the transition from Industry 4.0 to Industry 5.0?

The theoretical framework delves into this transition, emphasizing key themes such as technology, energy, sustainability, human-centric innovation, and workforce dynamics within shifting industrial and economic contexts. This study underscores the paradigm shift from Industry 4.0 to Industry 5.0, highlighting the crucial role of human-machine collaboration, sustainable practices, and social equity. In doing so, it draws out paths to a more sustainable, equitable, and resilient industrial future. Main findings emphasize ecological balance, the adaptability of business models, and the significance of inclusivity and workforce empowerment as essential drivers for long-term success in the evolving industrial landscape.

The rest of the paper is structured into the following key sections. Section 2 presents the theoretical foundations and contextual background of the study. Section 3 details and justifies the research design, methods employed, and considers alternative approaches. Section 4 compiles and presents the core findings. Section 5 critically examines and interprets the results in relation to existing literature. Section 6 offers final reflections, highlights the study's implications, and proposes directions for future research.

2. LITERATURE REVIEW

This section presents the theoretical background for this study, outlining the key concepts and intellectual perspectives that support the transition from Industry 4.0 to Industry 5.0, emphasizing paradigm shifts towards human-centered, sustainable innovation. It highlights future technologies and energy systems, sustainable business models, servitization, supply chain resilience, and empowered employees. The analysis aligns industrial economics with Society 5.0 and foresees an inclusive, resilient, and sustainable industrial future.

2.1. Technology and energy impact in the transition from Industry 4.0 to Industry 5.0

One of the major issues in transitioning from Industry 4.0 to Industry 5.0 is the consideration of energy footprints, i.e., how energy-friendly policies are adopted in higher-level technology platforms for promoting resilience, efficiency, and considerateness towards the environment. Industry accounts for 33% of greenhouse gas emissions, 40% of global solid waste, and 54% of global energy consumption (Hadi et al., 2023; Conti et al., 2016). Addressing these issues is aligned with Agenda 2030's SDGs that aim for a green and digital economy as sustainable development pillars (Carayannis et al., 2022). While Industry 4.0 technologies, such as IoT and AI, have reduced costs and increased productivity, their effect on sustainability is inconsistent, addressing micro-level issues while neglecting macro-level ones (Grybauskas et al., 2022; Ghobakhloo, Iranmanesh, Foroughi, et al., 2023). On the other hand, Industry 5.0 is centered on human-centricity, resilience, and sustainability to improve the quality of life by merging cutting-edge technology with socio-environmental goals (Botti & Baldi, 2025).

The transition from Industry 4.0 to Industry 5.0 is centered on human-machine collaboration, sustainability, and robot humanization. Industry 5.0 incorporates human abilities into robot design, creating professions such as robot assistants and chief robotics officers. "Mobile robot managers, machine programmers, robot assistants, process controllers, device teachers, and chief robotics officers" are a few examples (Kumar et al., 2023, p. 10). With the pandemic of COVID-19, Industry 4.0 technologies like IoT and big data alleviated supply chain and health fragility and introduced innovative solutions, and highlighted the core of resilience and sustainability (Kumar et al., 2023). However, Industry 4.0 digital transformation was non-human-centric (Grybauskas et al., 2022). Emerging technologies in Industry 5.0, such as cognitive cyber-physical systems, cognitive AI, and the Internet of Everything (IoE), enable real-time decision-making, reducing waste, and allowing circular economy operations, resulting in sustainable innovation (Ghobakhloo, Iranmanesh, Morales, et al., 2023; Mesjasz-Lech et al., 2024).

In Industry 5.0, human beings and intelligent systems work together to make decisions (Enang et al., 2023; Narkhede et al., 2024). Emerging technologies bring a human-centered approach that can transform the industrial process around the requirements of the human species (Grybauskas et al., 2022). This new process towards a Society 5.0 needs practices and decisions, as well as the development of structured policies for various stakeholders, to enhance the use of new digital technologies (Frederico, 2021). It emphasizes that development should be oriented towards a green economy with human well-being as the final purpose for using these technologies (Ivanov, 2023). Thus, Industry 5.0 takes into account the complexity of interactions between cultural, political, economic, and environmental factors to preserve the right to well-being for future generations (Ghobakhloo, Iranmanesh, Morales, et al., 2023). In fact, a prevalent argument in the discourse is robot and automation job displacement and the tenacity that technology brings to adaptation with disruption events (Enang et al., 2023). Besides the pandemic, increasingly evident climatic events have occasioned severe losses. How governments, businesses, and society generally respond to future events may be assisted by Industry 5.0 foresight.

2.2. From Industry 4.0 to Industry 5.0: A paradigm shift

Industry 4.0 saw the advent of intelligent technologies such as AI, IoT, robots, and big data analytics that transformed production efficiency and hyperconnectivity (Schwab, 2016; Ghobakhloo, Iranmanesh, Morales, et al., 2023). Industry 5.0, however, changes the attention to human-driven collaboration (Grybauskas et al., 2022), highlighting social sustainability and circular economy thinking (Ivanov, 2023). This paradigm places human well-being at the top, aligning technological advancement with societal and environmental objectives. New technologies support sustainable production, circular economies, and enhanced welfare, which produce industrial resilience and inclusivity (Eriksson et al., 2024; Marcon et al., 2022; Frederico, 2021; Yadav et al., 2020).

The transition from Industry 4.0 to Industry 5.0 represents a shift in focus from automation and efficiency to human-machine collaboration (Grybauskas et al., 2022). While Industry 4.0 prioritized machine-to-machine communication, Industry 5.0 centers humans in the process, recognizing the limitations of full automation in addressing societal and environmental challenges such as climate change and inequality (Ghobakhloo et al., 2024; Laddha & Agrawal, 2024; Mesjasz-Lech et al., 2024). Industry 5.0 aims to balance technology with human well-being (Enang et al., 2023), utilizing emerging technologies to drive sustainable changes in industrial practices (Ghobakhloo et al., 2022). This paradigm supports the UN SDGs by promoting responsible production, reducing waste, and ensuring decent work (Villar et al., 2023). In Industry 5.0, machines augment human capabilities, fostering creativity, problem-solving, and social sustainability (Gamberini & Pluchino, 2024; Narkhede et al., 2024; Ivanov, 2023).

Central to Industry 5.0's ambitions for sustainability is the circular economy, which replaces the unsustainable "take, make, dispose" model with one focused on waste prevention, resource efficiency, and regenerative strategies (Gruba et al., 2022). Based on recycling, reuse, and refurbishment, the idea is to keep products in circulation for longer and foster environmental resilience (Mesjasz-Lech et al., 2024; Eriksson et al., 2024; Marcon et al., 2022). Emerging technologies like IoT, AI, and blockchain are essential facilitators of circular economy mechanisms because they monitor the utilization of resources, optimize efficiency, and ensure ethical sourcing (Mesjasz-Lech et al., 2024; Grybauskas et al., 2022).

Under Industry 5.0, principles of circular economy provide greater priority to long-term environmental and social well-being (Hanif & Iftikhar, 2020). For instance, industries like electronics and automobile manufacturing are more and more adopting remanufacturing and product-as-a-service, reducing waste and ensuring maximum sustainability (Narkhede et al., 2023). These principles integrate human welfare with environmental stewardship, fostering resilient systems (Ghobakhloo et al., 2024; Laddha & Agrawal, 2024). The circular economy fosters sustainability through practices like remanufacturing and product-as-a-service models in electronics and automotive industries, reducing waste and enhancing resource efficiency (Narkhede et al., 2024; Ghobakhloo, Iranmanesh, Foroughi, et al., 2023; Narkhede et al., 2023). Industry 5.0 integrates these principles with technology for resilience and sustainability (Botti & Baldi, 2025; Corallo et al., 2024; Narkhede et al., 2023). Sustainable manufacturing prioritizes human welfare and mitigates environmental effects (Narkhede et al., 2024).

Social sustainability also lies at the core of Industry 5.0, aiming to create equitable systems that enhance the reduction of income disparities, education disparities, and disparities in resource access (Corallo et al., 2024; Frederico, 2021). Emphasizing equity, Industry 5.0 answers social challenges associated with technological progress, much like Society 5.0 (Frederico, 2021). New technologies enable social sustainability via increasing resilience and expanding the opportunities of vulnerable groups (Gamberini & Pluchino, 2024; Kumar et al., 2023). In agriculture, AI and IoT increase the efficiency of smallholder farmers and their food security through real-time data (Ivanov, 2023). Similarly, online learning platforms expand educational opportunities for rural and poor groups, promoting inclusivity (Gamberini & Pluchino, 2024; Enang et al., 2023). Yet, careful execution is important not to exacerbate current inequalities (Ghobakhloo et al., 2024; Grybauskas et al., 2022).

Besides sustainability, Industry 5.0 emphasizes human-centricity because, no matter the automated increase in productivity, human work must remain at the center of the process. The shift is centered on well-being, innovation, and employees' potential rather than mere efficiency and cost-saving (Eriksson et al., 2024; Ghobakhloo et al., 2024; Laddha & Agrawal, 2024; Marcon et al., 2022). Technologies like AI, robots, and augmented reality (AR) are enhancing human capability to do both machine-precise tasks and human-intuitive tasks (Van Erp et al., 2024; Enang et al., 2023). For instance, robots manage repetitive tasks, freeing humans for creative and decision-making roles, improving productivity, and reducing strain. In construction and healthcare, AI improves safety and accuracy by suggesting efficiencies and assisting diagnostics (Ivanov, 2023). Industry 5.0 also promotes social sustainability through fair wages, equitable conditions, and inclusive opportunities (Gamberini & Pluchino, 2024; Narkhede et al., 2024; Sharma & Gupta, 2024; Grybauskas et al., 2022; Hanif & Iftikhar, 2020).

Another cornerstone of Industry 5.0 is sustainable manufacturing, targeting the environmental impact of industrial growth (Gamberini & Pluchino, 2024; Narkhede et al., 2023). This involves minimizing waste, energy consumption, and greenhouse gas emissions while boosting productivity (Ghobakhloo, Iranmanesh, Morales, et al., 2023). Technologies like AI, IoT, and advanced robotics optimize production and resource efficiency (Eriksson et al., 2024). AI identifies inefficiencies, while IoT sensors enable predictive maintenance (Mesjasz-Lech et al., 2024; Ghobakhloo, Iranmanesh, Foroughi, et al., 2023; Yadav et al., 2023). Additive manufacturing reduces material waste through precise layer-by-layer construction (Mesjasz-Lech et al., 2024; Grybauskas et al., 2022). By prioritizing human-centric approaches, sustainable manufacturing promotes social responsibility, worker well-being, and community benefits (Sharma & Gupta, 2024; Ivanov, 2023; Hanif & Iftikhar, 2020).

As industries transition from Industry 4.0 to Industry 5.0, the nexus of human-centricity and sustainability represents a unique opportunity to reimagine the industrial space (Corallo et al., 2024). The circular economy, with its focus on efficiency of resources and minimization of waste, provides a framework for decoupling from the linear "take, make, dispose" model (Mesjasz-Lech et al., 2024; Ghobakhloo, Iranmanesh, Foroughi, et al., 2023). Technologies like AI, IoT, and blockchain may optimize green supply chains with prioritization for environment and social wellbeing (Eriksson et al., 2024; Frederico, 2021). Industry 5.0's human-centric approach fosters collaboration between humans and machines, where machines enhance human capabilities and productivity, improving working conditions and social sustainability (Narkhede et al., 2024). This shift leads to a more holistic industrial development, where sustainability and human well-being are prioritized, creating systems that are efficient, resilient, inclusive, and environmentally sustainable.

2.3. Industrial economics and technological development: The evolution of industrial revolutions

The confluence of industrial economics, industrial revolution, Society 5.0, and technological development is another relevant dimension of this study. Industrial economics deals with firms' behavior in the market, competition, and their long-term viability, involving studies of industry structure, firm behavior, and performance (Laddha & Agrawal, 2024; Xu et al., 2021). Industrial economics examines firm interaction and their impact on market results, which can tell us something about industrial growth, technological adjustments, and competitiveness (Sony et al., 2021; Ghobakhloo, 2020). This section offers valuable insights into the influence of emerging technologies on sustainability and economic growth, particularly in the context of Industry 4.0 to Industry 5.0 transformation (Narkhede et al., 2023; Grybauskas et al., 2022; Villar et al., 2023).

Economic institutions, technology, and manufacturing methods underwent profound transformations during industrial revolutions (Kumar et al., 2023; Ghobakhloo, Iranmanesh, Morales, et al., 2023). The First Industrial Revolution, starting in the late 1700s, introduced mechanization and steam power, transforming rural economies into industrial ones (Sindhwani et al., 2022). The Second Industrial Revolution in the late 19th and early 20th centuries saw mass production, electricity, and the internal combustion engine, driving unprecedented economic growth (Akundi et al., 2022; Sindhwani et al., 2022). The Third, or Digital Revolution, in the late 20th century spread digital technologies, changing information processing and production (Xu et al., 2021; Sindhwani et al., 2022). Industry 4.0 builds on this, incorporating AI, robotics, blockchain, IoT, and big data to create smart factories, enhancing efficiency, adaptability, and customization through automation and real-time data sharing (Yadav et al., 2020; Jefroy et al., 2022). In addition, Industry 4.0 emphasizes automation, real-time data sharing, and networked systems to create smart factories, enhancing adaptability, efficiency, and customization in manufacturing through seamless connectivity (Grybauskas et al., 2022).

2.4. Industry 5.0 and human-centric innovation: The rise of Society 5.0, sustainable business models, servitization, and workforce dynamics

As industries transition from Industry 4.0 to Industry 5.0, the focus shifts from automation and efficiency to human-centric innovation and sustainability (Corallo et al., 2024; Villar et al., 2023). Collaborative robots (cobots) are at the heart of this development, enhancing human-machine collaboration for tailor-made, sustainable, and inclusive industrial systems (Enang et al., 2023; Narkhede et al., 2024; Ivanov, 2023; Van Erp et al., 2024). Industry 5.0 integrates human creativity, ethics, and well-being into technological advancement to guarantee development benefits society in general (Ghobakhloo et al., 2024; Laddha & Agrawal, 2024; Hanif & Iftikhar, 2020). Suhardjo et al. (2024) also add that sound ethical governance increases the likelihood of sustainability plans having positive effects.

The Japanese government's Society 5.0 concept is also connected with Industry 5.0 and envisions a human-centered society where technologies like AI, IoT, and robots address societal issues and improve the quality of life (Huang et al., 2022; Grybauskas et al., 2022). Society 5.0 is "a human-centered society that balances economic development with the solution to social issues" (Chin, 2021, p. 2). It solves problems like aging societies, environmental sustainability, and economic inequalities, integrating cyberspace into physical space to improve societal well-being (Frederico, 2021; Deguchi et al., 2020; Villar et al., 2023). New technologies support human skill development, generating social well-being (Troisi et al., 2024; Carayannis et al., 2024; Narkhede et al., 2023; Ghobakhloo, Iranmanesh, Foroughi, et al., 2023).

Technological advancements drive the transition from Industry 4.0 to Industry 5.0, enabling new business models, production processes, and value creation mechanisms (Hadi et al., 2023). Emerging technologies such as AI, IoT, blockchain, and advanced robotics revolutionize industrial processes (Kumar et al., 2023; Yadav et al., 2020). They allow for intelligent factories featuring networked machines that exchange data, understand, and make decisions autonomously, resulting in more efficient, flexible production processes (Ghobakhloo et al., 2022; Narkhede et al., 2023). AI plays a pivotal role in optimizing operations, enhancing product quality, and improving decision-making (Gamberini & Pluchino, 2024). It also supports sustainability by reducing energy consumption, minimizing waste, and promoting eco-friendly practices (Cillo et al., 2022). IoT further enhances human-machine integration, enabling real-time data sharing to improve productivity, safety, and sustainability while creating "smart environments" (Botti & Baldi, 2025; Eriksson et al., 2024; Ivanov, 2023). IoT sensors can monitor machinery health, track environmental conditions, and ensure efficient resource use (Hadi et al., 2023). Blockchain technology facilitates ethical and sustainable behaviors by advancing trust, product authenticity, and ESG transparency (Tlili et al., 2023). Advanced robotics enhances precision, flexibility, and workplace safety through the support of labor-intensive processes and adapting to dynamic environments (Mesjasz-Lech et al., 2024; Sharma & Gupta, 2024; Hanif & Iftikhar, 2020).

Industry 5.0 also redesigns business models and organizational configurations (Corallo et al., 2024). Eco-friendly products like the circular economy and servitization focus on long-term relations and sustainability (Frederico, 2021). Servitization leads to product-as-service provision and user outcomes (Carayannis et al., 2024), and the circular economy focuses on waste reduction and enhancing resource productivity by reusing, repairing, and recycling (Mesjasz-Lech et al., 2024). The shift emphasizes human-machine collaboration, enabling workers to focus on creative tasks while automation handles routine work (Sharma & Gupta, 2024; Hanif & Iftikhar, 2020). Continuous upskilling, work-life balance, and employee well-being are central to this human-centric vision (Gamberini & Pluchino, 2024; Hussain et al., 2023; Enang et al., 2023; Chin, 2021).

Sustainability is the highest guiding ethos of development and adoption of technology that remains in the background for environmental purposes, yet improves human welfare in Industry 5.0 (Eriksson et al., 2024; Olsson et al., 2025; Marcon et al., 2022). Sustainable practices become even more crucial to success and business competitiveness in the long run, as well as compliance, as realized by businesses of today (Botti & Baldi, 2025). Sustainable innovation aims to enhance the standard of living, reduce emissions, and optimize resource utilization (Mesjasz-Lech et al., 2024; Troisi et al., 2024). Some of the principal areas of attention include energy-saving technology, eco-friendly materials, and renewable sources of energy. The shift from Industry 4.0 to Industry 5.0 is marked by technological advancement and an increased focus on sustainability and people-oriented innovation (Eriksson et al., 2024). Additionally, based on Industry 5.0 guidelines, Society 5.0 promotes the use of digital technology to improve quality of life as well as social issues (Carayannis & Morawska-Jancelewicz, 2022). Emerging technologies such as AI, IoT, blockchain, and robotics enable new business models, production methods, and value generation (Enang et al., 2023).

2.5. Sustainable manufacturing, supply chain resilience, social sustainability, and workforce empowerment

Sustainability refers to the unity and harmony between man and nature for sustaining future generations. The three pillars for sustainability include environment, economy, and society. Botti and Baldi (2025) recognize economic development, social justice, cultural heritage, and integrity of nature as the significant functions undertaken by sustainability. Sindhwani et al. (2022) propose a framework involving human values alongside technology for a bio-centric adaptive model of sustainability. This shift entails bioengineering, green strategies, and renewable energy to make society, the environment, and the earth sustainable (Sindhwani et al., 2020).

Sustainable manufacturing incorporates eco-friendly practices across a product's lifecycle, balancing economic, environmental, and social goals. The Industry 5.0 framework aligns with the UN's sustainability agenda, emphasizing the transformation of business models to achieve the 17 SDGs (Ghobakhloo et al., 2022). The transition from mass production to mass customization enables personalized products and services, improving customer experience while enhancing productivity, efficiency, and waste reduction (Frederico, 2021; Gamberini & Pluchino, 2024; Villar et al., 2023). Sustainable supply chains prioritize economic, social, and environmental sustainability while fostering societal responsibility and equitable development (Laddha & Agrawal, 2024; Villar et al., 2023). This approach enhances supply chain adaptability, particularly for smaller-scale operations, improving resilience and transparency (Ghobakhloo et al., 2024). Smaller-scale supply chains can mitigate vulnerabilities through transparent governance practices, such as eco-labeling in global value chains (Singer & van der Ven, 2019).

Additionally, sustainable manufacturing integrates cleaner technologies, reduced energy consumption, optimized material use, recycling, and fostering societal citizenship behavior (Ghobakhloo Iranmanesh, Foroughi, et al., 2023). However, small and medium-sized enterprises (SMEs) face challenges such as high costs for technology upgrades and process redesigns (Narkhede et al., 2024; Narkhede et al., 2023). Circular manufacturing extends product lifecycles and minimizes waste, supported by green supply chain management (GSCM) and reverse logistics facilitated by AI, IoT, and data analytics (Mesjasz-Lech et al., 2024; Villar et al., 2023).

Coordinating sustainability across complex, multi-stakeholder supply chains faces challenges like employee resistance and inconsistent regulations (Laddha & Agrawal, 2024; Narkhede et al., 2024; Narkhede et al., 2023). Overcoming these barriers requires integrating human and machine capabilities while promoting renewable energy and resource-efficient products (van Erp et al., 2024). Sustainable business model innovation (SBI) and sustainable employment practices (SEP) align sustainability with employee satisfaction (Ghobakhloo, Iranmanesh, Morales, et al., 2023). CDT optimize processes, resource efficiency, and adaptability, driving sustainable industrialization (Sharma & Gupta, 2024).

Social sustainability is at the core of Industry 5.0, prioritizing human needs, rights, and equity, and workforce empowerment through upskilling, reskilling, and tailor-made development schemes. These schemes enhance occupational safety, productivity, and job satisfaction, fostering micro-socioeconomic sustainability. Democratic dialogue plays an essential part in reducing problems linked with technological innovation (Ghobakhloo et al., 2024; Gamberini & Pluchino, 2024). Following the UN SDGs, specifically good health and well-being, Industry 5.0 considers psychological workplace well-being and includes human-centered approaches to build resilience in evolving industrial ecosystems (Grybauskas et al., 2022).

In the face of issues such as data privacy concerns, increased costs of production, and supply chain complexity (Frederico, 2021), particular career approaches, human resources (HR) training, and sustainability culture building programs (Carayannis et al., 2024; Piccarozzi et al., 2024) are required to overcome them. Society 5.0 is synchronized with Industry 5.0, unifying cyberspace and the real world for enhanced quality of life through human-centric innovation (Tilli et al., 2023; Troisi et al., 2024; Carayannis & Morawska-Jancelewicz, 2022).

2.6. Future visions: Resilience in Industry 5.0 and beyond

Resilience is a vital component of Industry 5.0, emphasizing adaptability and responsiveness in the era of global crises and geopolitical shifts (Ghobakhloo, Iranmanesh, Morales, et al., 2023). It involves the ability of supply chains to maintain manufacturing ecosystem stability under the impact of disruption and uncertainty, such as anticipation, adaptation, and recovery skills (van Erp et al., 2024). Resilience has a very close connection with organizational culture, leadership, innovation, product development, technology investments, diversification of revenues, and managerial ability (Botti & Bladi, 2025). During Industry 4.0, resilience primarily benefited large tech companies and digitalization pioneers at the expense of small businesses. Meanwhile, Industry 5.0 attempts to democratize digitalization such that small and medium-sized enterprises (SMEs), as well as large-scale enterprises, can enact adaptable processes facilitating operations, providing basic human necessities, and augmenting societal resilience (Enang et al., 2023; Ghobakhloo et al., 2023). Villar et al. (2023) identify two prominent goals of Resilience 5.0: enhancing workforce self-resilience and achieving system resilience in human-machine systems in intelligent manufacturing.

Self-resilience refers to an individual's ability to recover from adversity, which is based on cognitive, psychological, emotional, and physical factors (Villar et al., 2023). System resilience refers to the capacity of human-machine systems to resist changing demands such that combined responses are realized to dynamic factory and supply chain demands (Villar et al., 2023; Sindhwani et al., 2022). Manufacturing resilience (MNR) enables manufacturers to recover and bounce back from disruptions rapidly. Decentralized production encourages agility, allowing operations to scale, shift product mixes, and reconfigure at low cost. Blockchain and CDT also further enhance organizational resilience (Ghobakhloo et al., 2023).

While Industry 4.0 revolutionized manufacturing through automation and cost optimization, it often overlooked human needs, creating disparities based on regional economic structures (Jefroy et al., 2022; Grybauskas et al., 2022; Villar et al., 2023). Industry 5.0 seeks to rectify this imbalance by reintroducing human-centric priorities into manufacturing systems. The Fifth Industrial Revolution, the "Age of Augmentation", builds on Industry 4.0 by blending technological advancements with societal transformation. It focuses on six key areas: human-machine interaction, bio-inspired technologies, CDT, big data analytics, AI, and renewable energy efficiency (Gamberini & Pluchino, 2024; Ghobakhloo, Iranmanesh, Morales, et al., 2023; Jefroy et al., 2022; Laddha & Agrawal, 2024; Narkhede et al., 2024; Villar et al., 2023). Industry 5.0 emphasizes human intellect and interaction, integrating interdisciplinary education, innovation management, and system integration to foster a human-centric ecosystem (Narkhede et al., 2024).

By merging human cognitive abilities with advanced technologies, it creates a future where humans handle critical thinking tasks while machines manage repetitive processes. Yeung (2023) suggests that integrating Web 3.0 and SDGs creates value in responsible businesses' learning. Sustainability spans social, economic, environmental, and institutional dimensions, enhancing productivity and value creation (Frederico, 2021). Villar et al. (2023) envision the sixth industrial revolution as a hyper-connected, customer-driven system with dynamic, antifragile supply chains promoting societal integration. In addition, Ivanov (2023) highlights resilience as integral to sustainability, supported by human-centric ecosystems in agriculture, education, healthcare, and housing. Smart cities leveraging IoT, data analytics, and sustainable practices optimize energy, waste, and transportation, fostering community well-being (Corallo et al., 2024; Kumar et al., 2023).

Villar et al. (2023) propose the sixth industrial revolution, a hyper-connected, customer-driven system with dynamic supply chains and data flow, promoting antifragile manufacturing and societal integration. This is an ideological concept with "ubiquitous, customer-driven, virtual, antifragile manufacturing. It will encompass a customer-focused ethos and hyper-connected industries with dynamic supply chains where data flows across domain" (Villar et al., 2023, p. 24).

3. RESEARCH METHODOLOGY

3.1. Research method

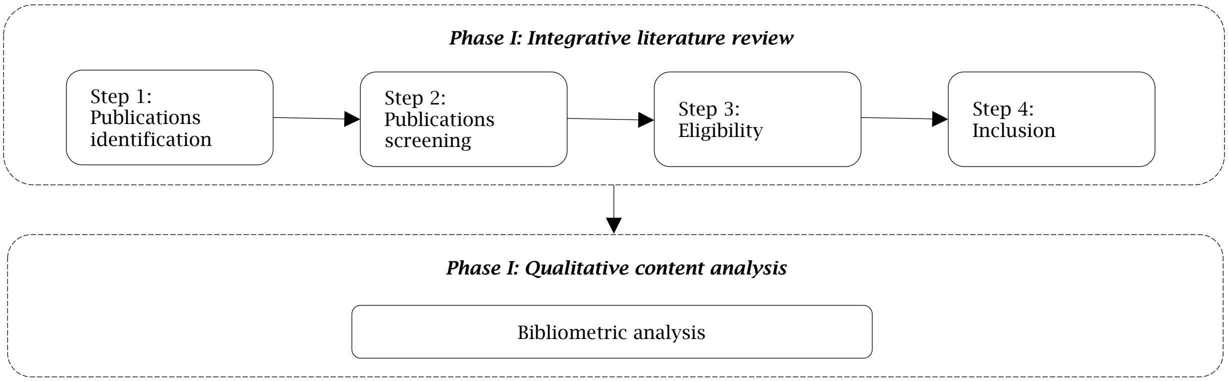
To evaluate the extent to which emerging technologies enhance sustainability in the pathway from Industry 4.0 to Industry 5.0, we had to identify major literature subjects and threads (Hadi et al., 2023). To do so, a mixed methods approach was employed in two phases. In Phase I, a bibliometric analysis through a thematic integrative literature review (ILR) was employed to appraise research work related to our objective (Dewey & Drahota, 2016; Gough et al., 2012), with emphasis on research standards based on evidence (Ghobakhloo et al., 2024). ILR was introduced by Torraco (2005) and evaluates, interprets, and synthesizes representative literature on a subject in a cohesive manner to produce fresh frameworks and viewpoints. To produce new knowledge, an ILR integrates the state of knowledge currently available (Cho, 2022). A thematic ILR, according to Creswell (2008), is one in which the researcher uses the literature to find themes and patterns in research areas and then discusses those themes, generally mentioning the studies that inspired them.

Consistent with this study, Whittemore and Knafl (2005) support that an ILR is appropriate for a research sphere that is more generally focused on a phenomenon of interest than a systematic review. It permits a variety of studies, some of which may include theoretical and methodological literature, to answer the review's goal as well as assisting with a variety of research tasks, including idea definitions, theory reviews, and methodological analysis (Broome, 2000; Toronto & Remington, 2020).

3.2. Methodology structure and operationalization

A graphical depiction of the data was used in the analysis to highlight important traits and the connections between the analytical themes that emerged in the included papers. Second, qualitative content analysis was employed to assess the literature pertinent to the study, involving content and thematic synthesis (Enang et al., 2023). Figure 1 shows the methodology outline.

Figure 1. Methodology outline



Source: Authors' elaboration.

Our methodology is divided into two phases. Phase I comprehends the ILR utilizing the preferred reporting items for systematic reviews and meta-analyses, PRISMA approach (Moher et al., 2009). In ILR, the approach to the literature search should be systematic and thorough, utilizing two or more methods, and PRISMA can be used to improve the reporting of the search (Toronto & Remington, 2005; Moher et al., 2009). Multiple studies in different areas have used PRISMA to report literature search, e.g., Moran et al. (2014), support strategies for health care practitioners; Antwi et al. (2021), achievements in water and air pollution; Andersson et al. (2022), ethics education for healthcare professionals; Perez-Brescia (2022), Hispanics' access to health care during the COVID era; Onur et al. (2024), digital technologies in waste recycling.

Phase I comprises four steps: 1) identification of relevant publications, 2) screening, 3) eligibility, and 4) inclusion. Inclusion and exclusion criteria were applied during steps 2 and 3. Database searches with keyword filters identified relevant papers. Abstracts and manuscripts were reviewed, duplicates removed, and publications aligned with the study's objectives selected. The segmented process for determining suitable works is detailed in Table 1, while exclusion criteria applied during screening are summarized in Table 2.

Table 1. Search process segmentation

Database			***Research string***			
			"Industry 5.0" AND "Technolog*" AND "Sustainabilit*"	***"Industry 4.0" AND "Industry 5.0" AND "Technolog*" AND "Sustainabilit*"***	***"Industry 5.0" AND "Emerging Technolog*"***	***Overall***
Scopus	Document type (Article/Review)		153	87	25	265
	Research area	Management, Business, Accounting	47	31	5	83
		Economics, Econometrics, Finance	5	3	0	8
	Language: English		50	33	5	88
	Scopus overall		300	164	59	523
Web of Science	Document type (Article/Review)		131	72	27	230
	Research area	Management				
		Business, Economics	25	15	2	42
	Language: English		25	15	2	42
	Web of Science overall		146	80	30	256

Note: Query: 2024/06/11.
Source: Authors' elaboration.

Overall, 256 manuscripts were considered from Web of Science (WoS), and 523 from Scopus, totaling 779. From those, 230 from WoS and 259 from Scopus (495 in total) were selected after DTB, BER, PER, LAN, and FTK exclusion criteria (see Table 2). Those manuscripts were in the Business/Economics category in WoS, and Management, Business, and Accounting, and Economics, Econometrics, and Finance in Scopus.

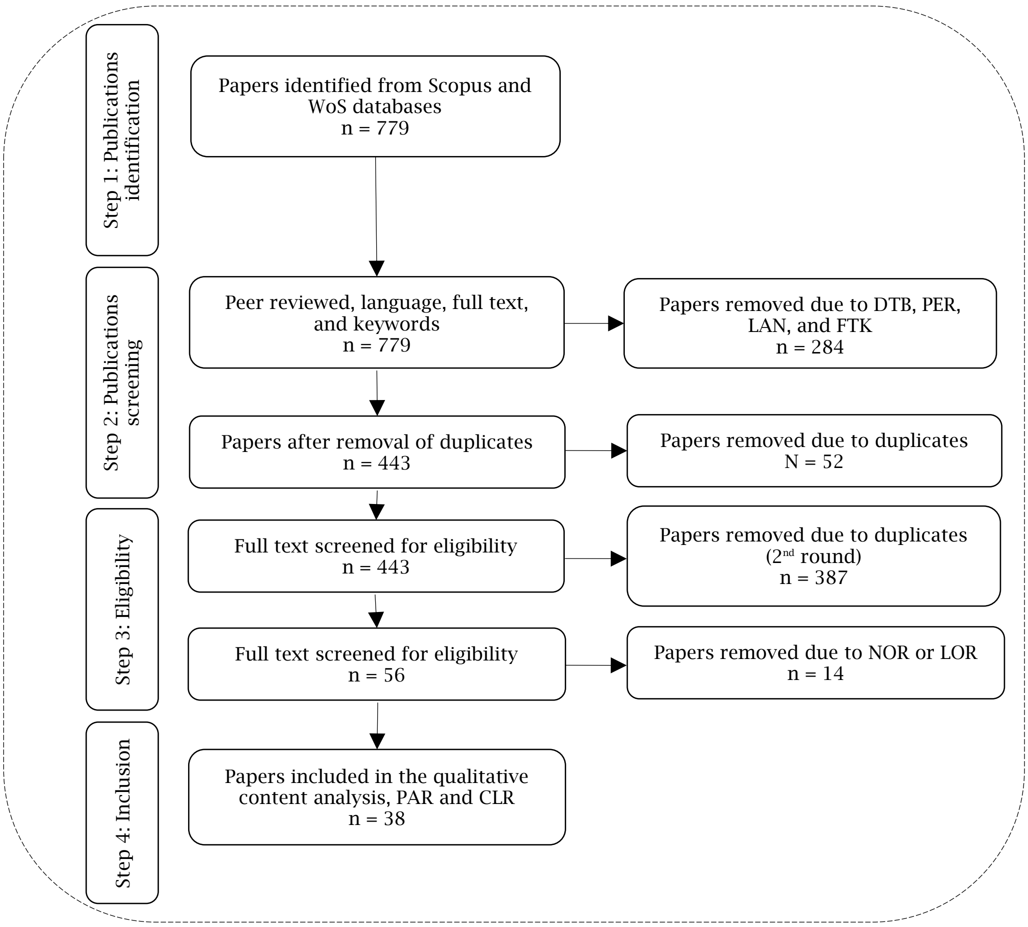
Table 2. Exclusion and inclusion criteria

Exclusion		
Criteria	***Acrostic***	***Description***
Database	DTB	The paper is not from Scopus or WoS.
Business/Economics related	BER	The paper is not from business/economics-related fields.
Peer reviewed	PER	The paper is not peer reviewed.
Language	LAN	The text is not in English.
Full text and keywords	FTK	Paper without full text and/or keywords.
Nonrelated	NOR	The paper does not discuss emerging technologies, sustainability, Industry 4.0, or Industry 5.0.
Loosely related	LOR	The main text does not explore the context of emerging technologies and sustainability in Industry 4.0 and/or 5.0; Emerging technologies, sustainability, Industry 4.0, and/or 5.0 are in keywords only.
Inclusion		
Criteria	***Acrostic***	***Definition***
Partially related	PAR	The paper discusses broader contextual development in Industry 4.0 and/or 5.0 without specifying emerging technologies and/or sustainability.
Closely related	CLR	The paper is specifically related to pathways from Industry 4.0 and 5.0 and addresses emerging technologies and/or sustainability.

Source: Authors' elaboration based on Enang et al. (2023).

The ILR applied PRISMA guidelines, selecting peer-reviewed English articles on Industry 4.0/5.0, emerging technologies, and sustainability. Titles, abstracts, and full texts were screened, with eligible studies analyzed in Phase II. See Figure 2 for details.

Figure 2. PRISMA flow chart



Source: Authors' elaboration based on PRISMA (http://www.prisma-statement.org/) and Enang et al. (2023).

A four-step review process following PRISMA analysis was conducted. In Step 1 (Identification), 779 manuscripts were selected. Step 2 (Screening) applied DTB, BER, PER, LAN, and FTK exclusion criteria, excluding 284 publications. In Step 3 (Eligibility), abstract analysis and key phrases removed 52 duplicates. Thorough content examination excluded 387 manuscripts, leaving 56 eligible papers. Step 4 (Inclusion) applied NOR and LOR criteria, rejecting 14 more papers. Ultimately, 38 manuscripts meeting PAR and CLR inclusion criteria were included in the review.

During Phase II, bibliometric analysis complemented qualitative content analysis. VOSviewer (Van Eck & Waltman, 2022) was chosen for its effectiveness in visualizing research authorship, sources, and keywords (Hadi et al., 2023). The qualitative analysis included line-by-line coding, descriptive theme construction, and analytical theme development (Thomas & Harden, 2008; Enang et al., 2023). Key themes were identified through a detailed review of narratives on sustainability and emerging technologies tied to the transition from Industry 4.0 to Industry 5.0.

3.3. Alternative methods

Alternative research methods include systematic literature review (SLR), meta-analysis, and narrative review. A SLR is a comprehensive method that involves identifying, selecting, and critically assessing research to answer a formulated research question. It is aimed at reducing errors that can lead to deviations from truthful results (Liberati et al., 2009). Systematic reviews can evaluate if the effects of a relationship are consistent and identify reasons for discrepancies in study findings to address the overall strength of the evidence. The main step of a systematic review includes 1) formulating a review question and search strategy, 2) searching for studies using multiple databases and sources, 3) selecting studies, extracting data, and assessing bias risk, 4) analyzing data in both quantitative and qualitative methods, 5) presenting results, and 6) interpreting results and drawing conclusion (Paré & Kitsiou, 2017). It involves planning well-thought-out research with a specific focus or defined questions. Pittway (2008) outlines seven key principles of SLRs, including transparency, clarity, integration, focus, equality, accessibility, and coverage.

Many systematic reviews utilize statistical methods to combine the findings of separate studies into a single summary. These reviews are known as meta-analyses and employ specific data extraction procedures and statistical approaches to calculate the effect size for each outcome of interest, along with a confidence interval that addresses the uncertainty surrounding the point estimate. It is viewed as a powerful tool for deriving meaningful research conclusions. If authors have conducted one or more meta-analyses, it is wise practice to present results as an estimated effect across studies with a confidence interval (Paré & Kitsiou, 2017).

The traditional way of viewing literature, and the simplest, that is skewed toward qualitative interpretation is a narrative review. It attempts to summarize previously written information on a topic but does not cumulate knowledge from what is reviewed. The goal is to identify a range of available literature and a gap where new literature will be able to fill. This type of review can be considered opportunistic at times, as it does not involve a systematic or exhaustive search. Additionally, it may also involve the removal of studies in which the researcher has little interest (Davies, 2000).

4. RESULTS

4.1. Integrative review

The transition from Industry 4.0 to Industry 5.0 is highlighted through an analysis of 38 manuscripts, comprising 74% articles and 26% reviews. These studies explore emerging technologies and their potential to transform enterprises into ecologically and socially sustainable entities. The term "Industry 5.0", introduced by the European Commission in 2021, gained prominence following the publication of a comprehensive report outlining Europe's vision for moving beyond the limitations of Industry 4.0 (Ivanov, 2023; Hadi et al., 2023).

Industry 4.0 focuses on digitalization, automation, and advanced technologies to enhance productivity and reduce costs (Ghobakhloo, Iranmanesh, Foroughi, et al., 2023). However, the European Commission emphasizes placing humans at the center of economic activity. Industry 5.0 prioritizes human interaction and sustainability, aiming to create resilient and sustainable industrial systems while addressing social and ecological concerns (Carayannis & Morawska-Jancelewicz, 2022; Breque et al., 2021).

4.2. Qualitative content analysis

Table 3 lists the top ten articles in the Business and Economics portfolio in terms of citations. Among the writers under the Industry 5.0 subject, it is interesting to notice that Sindhwani et al. (2022) have 97 citations, Ivanov (2023) has 157 citations, and Carayannis and Morawska-Jancelewicz (2022) have 167 citations.

Table 3. Top 10 most cited articles (Part 1)

No.	*Authors*	*Title*	*Source Title*	*Cited by*	*Year*
1	Carayannis and Morawska-Jancelewicz	The futures of Europe: Society 5.0 and Industry 5.0 as driving forces of future universities	*Journal of the Knowledge Economy*	167	2022
2	Ivanov	The Industry 5.0 framework: viability-based integration of the resilience, sustainability, and human-centricity perspectives	*International Journal of Production Research*	157	2023
3	Sindhwani, Afridi, Kumar, Banaitis, Luthra, and Singh	Can Industry 5.0 revolutionize the wave of resilience and social value creation? A multi-criteria framework to analyze enablers	*Technology in Society*	97	2022
4	Grybauskas, Stefanini, and Ghobakhloo	Social sustainability in the age of digitalization: A systematic literature Review on the social implications of Industry 4.0	*Technology in Society*	79	2022
5	Frederico	From Supply Chain 4.0 to Supply Chain 5.0: Findings from a systematic literature review and research directions	*Logistics*	75	2021

Table 3. Top 10 most cited articles (Part 2)

No.	Authors	Title	Source Title	Cited by	Year
6	Jefroy, Azarian, and Yu	Moving from Industry 4.0 to Industry 5.0: What are the implications for smart logistics?	*Logistics*	68	2022
7	Karmaker, Bari, Anam, Ahmed, Ali, de Jesus Pacheco, and Moktadir	Industry 5.0 challenges for post-pandemic supply chain sustainability in an emerging economy	*International Journal of Production Economics*	49	2023
8	Ghobakhloo, Iranmanesh, Morales, Nilashi, and Amran	Actions and approaches for enabling Industry 5.0-driven sustainable industrial transformation: A strategy roadmap	*Corporate Social Responsibility and Environmental Management*	44	2023
9	Ghobakhloo, Iranmanesh, Foroughi, Babaee Tirkolaee, Asadi, and Amran	Industry 5.0 implications for inclusive sustainable manufacturing: An evidence-knowledge-based strategic roadmap	*Journal of Cleaner Production*	31	2023
10	Tlili, Huang, and Kinshuk	Metaverse for climbing the ladder toward 'Industry 5.0' and 'Society 5.0'?	*Service Industries Journal*	31	2023

Source: Authors' elaboration.

The sources for the portfolio are shown in Table 4, demonstrating the portfolio's applicability and highlighting the rising interest in Industry 5.0, related emerging technologies, and their use to strengthen the green economy.

Table 4. Manuscript sources

No. of documents	Source title	Impact factor (2023)	Cite score (2023)
4	*Journal of Cleaner Production*	9.7	20.4
4	*Logistics*	3.6	6.6
2	*European Journal of Innovation Management*	5.1	10.4
2	*IEEE Transactions on Engineering Management*	6.1	3.5
2	*International Journal of Production Research*	9.2	18.1
2	*Technological Forecasting and Social Change*	12.9	21.4
2	*Technology in Society*	10.1	17.9
1	*Asia-Pacific Journal of Business Administration*	3.8	7.2
1	*Australian Journal of Career Development*	1.4	2.2
1	*Business Strategy and Development*	4.8	5.8
1	*Corporate Social Responsibility and Environmental Management*	8.3	17.2
1	*Engineering Management in Production and Services*	2.6	3.4
1	*Ibima Business Review*	0,35	0.8
1	*International Journal of Production Economics*	9.8	21.4
1	*Journal of Construction Engineering and Management*	5.1	8
1	*Journal of Strategy and Management*	3.1	6.3
1	*Journal of Technology Transfer*	4.2	10.8
1	*Journal of The Knowledge Economy*	4.0	3.9
1	*Operations Research Forum*	0,74	1.5
1	*Rausp Management Journal*	2.0	3.3
1	*Service Industries Journal*	9.4	16.4
1	*Supply Chain Management*	7.9	16.7
1	*TQM Journal*	3.8	9.1
1	*Technological Sustainability*	-	1.6
1	*Technovation*	11.1	15.1
1	*Tehnicki Glasnik*	1.3	1.5
1	*Worldwide Hospitality and Tourism Themes*	2.2	4.6

Source: Authors' elaboration.

5. DISCUSSION

5.1. The pathway from Industry 4.0 towards Industry 5.0

Industry 4.0 was conceived in Germany's 2011 Hannover Fair, growing in significance as Smart Factory technologies were adopted across sectors (Frederico, 2021; Jefroy et al., 2022). It emphasized digitalization and hyper-connectedness as drivers of economic competitiveness, the Fourth Industrial Revolution (Schwab, 2016; Enang et al., 2023). Industry 4.0 helped countries reindustrialize and keep capital in place with reshoring, incorporating technologies that preferred automation and productivity using hyperconnected products, machines, and consumers (Troisi et al., 2024). Criticism, however, targets its endorsement of neoliberal capitalism, prioritizing profit over sustainability and welfare (Enang et al., 2023). Industry 5.0 includes human-centric, sustainable alternatives for resource depletion and climate reversal (Ghobakhloo, Iranmanesh, Foroughi, et al., 2023; Ghobakhloo et al., 2024).

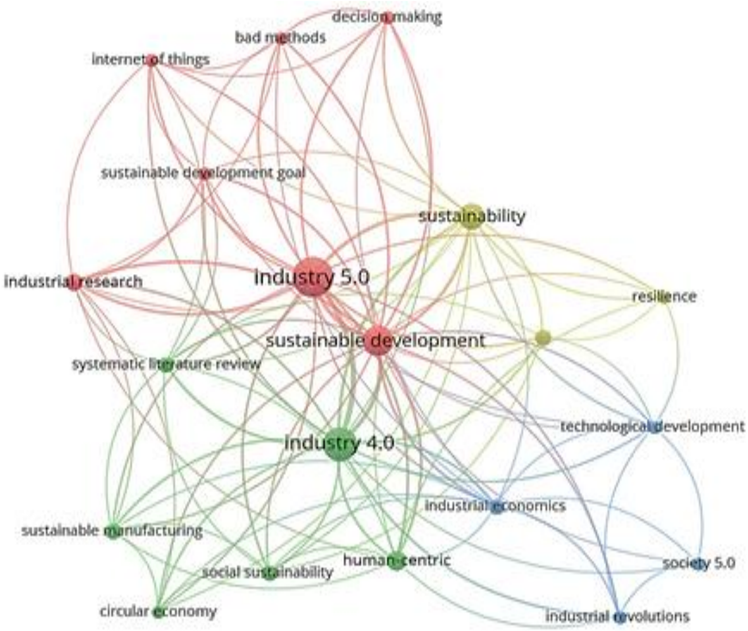
5.2. Industry 5.0: The context of sustainability, human centricity, and the scope of emerging technologies

Industry 5.0 builds upon Industry 4.0 by extending its focus on competitiveness and innovation to include human-machine collaboration, resilience, and sustainability (Kumar et al., 2023). Industry 5.0 integrates AI, IoT, blockchain, and CDT to create human-centric, sustainable ecosystems (Yadav et al., 2020). Machine learning and AI maximize the utilization of energy and minimize waste (Gamberini & Pluchino, 2024), and IoT allows for data-driven, real-time supply chain sustainment for decisions (Eriksson et al., 2024). Blockchain is ethical sourcing and circularity compatible, and CDT enables greater productivity without increasing damage to the environment (Mesjasz-Lech et al., 2024; Ghobakhloo, Iranmanesh, Foroughi, et al., 2023). Industry 5.0 human centrality ensures greater inclusion, health, and fit with greater society and nature-oriented goals (Frederico, 2021; Corallo et al., 2024).

5.3. Industry 4.0 and its trajectory towards Industry 5.0: Sustainability and human centricity through emerging technologies cluster analysis

The shift from Industry 4.0 to 5.0 integrates AI, IoT, blockchain, and CDT with human-centric, ethical, and sustainable goals, addressing climate urgency and promoting inclusive growth (Carayannis & Morawska-Jancelewicz, 2022; Villar et al., 2023). ILR keyword analysis reveals four key clusters linking these transformative paradigms (Figure 3).

Figure 3. Network of keywords (defined by authors) related to Industry 5.0



Source: Authors' elaboration using Scopus and Web of Science references in VOSviewer software.

It is noteworthy that although this architecture is closer to Industry 5.0, Figure 3 shows how Industry 4.0 and Industry 5.0 are connected through sustainable development. The number of times an event appears in the texts determines the network's strength. The clusters and corresponding keyword themes from the VOSviewer analysis are shown in Table 5 below.

Table 5. Keywords clusters

Cluster	*Themes*
1st cluster	• Bad methods • Decision making • Industrial research • Industry 5.0 • Internet of Things • Sustainable development • Sustainable development goal
2nd cluster	• Circular economy • Human-centric • Industry 4.0 • Social sustainability • Sustainable manufacturing • Systematic literature review
3rd cluster	• Industrial economics • Industrial revolutions • Society 5.0 • Technological development
4th cluster	• Literature review • Resilience • Sustainability

Source: Authors' elaboration.

These clusters provide a comprehensive view of the technological and human-centric forces driving sustainability and innovation in modern industry. The first cluster focuses on the technological and energy aspects of the Industry 4.0 to 5.0 shift (Hadi et al., 2023; Conti et al., 2016), linking decision-making, industrial research, and sustainable development with how emerging technologies and energy strategies support sustainability goals (Ghobakhloo, Iranmanesh, Morales, et al., 2023; Mesjasz-Lech et al., 2024; Carayannis & Morawska-Jancelewicz, 2022).

The second cluster explores the Industry 4.0 to 5.0 transition through circular economy, human-centeredness, and social sustainability (Ghobakhloo, Iranmanesh, Foroughi, et al., 2023; Ghobakhloo et al., 2024). It shows how AI, IoT, robotics, CDT, and big data support inclusive, sustainable production (Schwab, 2016; Ghobakhloo, Iranmanesh, Morales, et al., 2023), shifting focus from efficiency to human well-being, circular design, and ecosystem care (Eriksson et al., 2024; Frederico, 2021; Yadav et al., 2020).

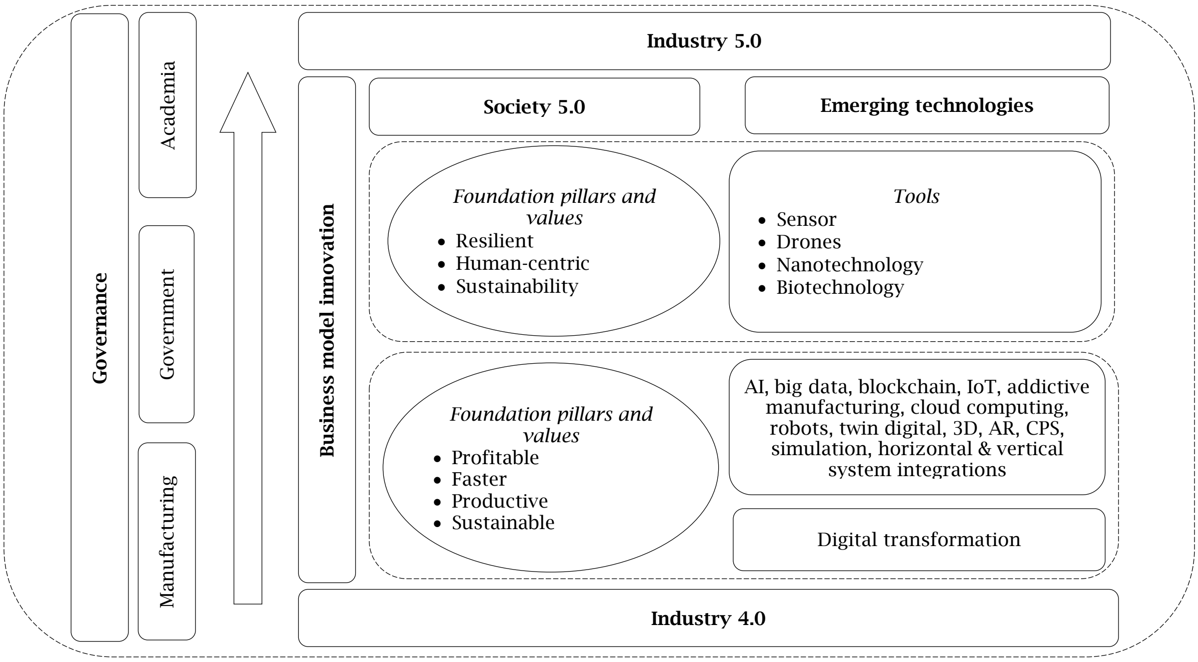
The third cluster addresses industrial economics, technological advancement, and Society 5.0 (Xu et al., 2021; Laddha & Agrawal, 2024). It examines how firms navigate technological revolutions, enhance competitiveness, and sustain economic growth (Ghobakhloo, 2020), highlighting the role of industrial structure, conduct, and performance in shaping sustainable outcomes and fostering economic resilience through innovation (Narkhede et al., 2023; Grybauskas et al., 2022; Villar et al., 2023).

Lastly, the fourth cluster emphasizes sustainability, resilience, and conceptual thinking (Botti & Baldi, 2025). It is based on environmental, economic, and social factors, emphasizing circular processes, cultural identity, resilience, and bio-centric resilience (Sindhwani et al., 2022; Ivanov, 2023). It advances sustainability as a vision for the long-term equilibrium between human development and planetary well-being (Sindhwani et al., 2020).

5.4. Framework: Transition from Industry 4.0 to Industry 5.0

Through an extensive literature review and cluster analysis, we developed a framework illustrating the transition from Industry 4.0 to 5.0 (Figure 4). A key challenge lies in governing diverse organizational objectives. The Triple Helix theory (Leydesdorff & Etzkowitz, 1998) highlights the roles of government, industry, and universities in innovation, with universities providing human capital to renew ideas, foster technology, and drive entrepreneurship (Etzkowitz & Zhou, 2017).

Figure 4. Transition from Industry 4.0 to Industry 5.0



To guide Industry 4.0 and 5.0 transformations, the quintuple helix model is essential, aligning entrepreneurship and venture capital to take advantage of emerging technologies (Capetillo et al., 2021). Nelson and Nelson (2002) emphasize social technologies in anchoring innovations, while Mowery and Rosenberg (1999) emphasize market size and income distribution. Industry 4.0 emphasizes productivity but lacks human-centered approaches (Ericksson et al., 2024). Industry 5.0 changes governance to well-being and sustainability (Ivanov, 2023). Schumpeter's (2010) creative destruction and Kondratieff and Stolper's (1935) cycles illustrate the manner in which innovations replace previous systems (Asif et al., 2023). Business model innovation (BMI) makes sustainability a part of Industry 5.0, taking the triple bottom line of People, Planet, Profit to a new height (Evans, 2017; Yip & Bocken, 2018). With the assistance of AI, IoT, and CDT, BMI encourages cleaner energy and circular economies (Kumar et al., 2023; Carayannis & Morawska-Jancelewicz, 2022), converging with lean production for wider societal impact (Ericksson et al., 2024; Ghobakhloo, Iranmanesh, Foroughi, et al., 2023; Mesjasz-Lech et al., 2024).

6. CONCLUSION

This study examined the evolution from Industry 4.0 to Industry 5.0 in relation to the implementation of new technologies for sustainability and human-centric innovation. Our research question, "To what extent do new technologies influence sustainability and human-machine collaboration in the transition from Industry 4.0 to Industry 5.0?" is addressed by revealing the limitations and advancements of these industrial paradigms. Industry 4.0 is concerned with efficiency via technologies such as IoT, AI, and robotics. However, its benefits are largely confined to the techno-economic domain, often at the expense of environmental sustainability and social concerns. On the contrary, Industry 5.0 closes this shortcoming by bringing together technological innovation and human values with ecological responsibility and social equity to bridge this gap in work towards a balanced and more inclusive form of industrial transformation, promoting circular economies, eco-friendly production, and social labor forces. Technologies like cognitive AI, cyber-physical systems, and smart materials enable real-time decision-making, personalization, and sustainable ecosystems. The COVID-19 pandemic emphasized the relevance of resilience, with the accelerated adoption of digital and vindication of the necessity for Industry 5.0's human-machine partnership. This paradigm shift fosters social equity and workforce empowerment and raises productivity and environmental stewardship.

The study highlights some of the implications. Firstly, human-machine collaboration improves work innovation and satisfaction. Secondly, ecological equilibrium is enhanced through sustainable practices. Thirdly, BMI should focus on flexibility, customer requirements, and resource optimization. Fourthly, social sustainability must provide inclusivity and professional growth.

These areas must be examined in future studies: affective and cognitive AI, renewable energy integration, and circular economy best practices. The BMI strategy must also be created to respond to worldwide challenges. The downside is the industrial scope of the research, excluding sectors like healthcare and education. Quantitative methods and broader fields of application can also improve future studies.

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