Do the Innovative Technological Advancements Foster the Green Transition Pathways for Industry 5.0? A Perspective towards Carbon Neutrality

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Abstract

Purpose: Industries have been the most significant contributor to carbon emissions since the beginning of the Industrial Revolution. The transition to Industry 5.0 (I5.0) marks a pivotal moment in the industrial revolution, which aims to reconcile productivity with environmental responsibility. As concerns about the decline of environmental quality increase and the demand for sustainable industrial methods intensifies, experts recognize the shift towards the I5.0 transition as a crucial turning point.

Design/Methodology/Approach: This review study explores the convergence of green technological advancements with the evolving landscape of I5.0, thereby presenting a roadmap towards carbon neutrality. Through an extensive analysis of literature spanning from 2012 to 2024, sourced from the Scopus database, the research study unravels the transformative potential of green technological innovations, artificial intelligence, green supply chain management, and the metaverse.

Findings: The findings underscore the urgent imperative of integrating green technologies into the fabric of I5.0, highlighting the opportunities and challenges inherent in this endeavour. Furthermore, the study provides insights tailored for policymakers, regulators, researchers, and environmental stakeholders, fostering informed decision-making towards a carbon-neutral future.

Originality/Value: This review serves as a call to action, urging collective efforts to harness innovation for the betterment of industry and the environment.

Keywords: Circular Economy; Environment Sustainability; Metaverse; Sustainable Development; Green Finance; Technological Innovations

Paper type- Review Paper

1.1 Introduction

Industrial activities contribute approximately 21% of global carbon emissions, creating an environmental footprint that necessitates immediate attention (IRENA 2023). The need for cohesive and globally coordinated policies to incentivize a transition to green economies is evident. This underscores the necessity for policy frameworks that foster a more robust commitment to technology-driven sustainable initiatives. As per the IPCC (2023) and UNEP (2022), carbon neutrality is the solution to address the threat of climate change as the earth is approaching its *'tipping point'*. Hence, it becomes essential for the I5.0 transition to consider the carbon neutrality targets for 2050. In the wake of accelerated industrialization, the persistent challenge of mitigating carbon emissions and curbing the adverse effects of climate change has become an urgent imperative for sustainable development (Baig and Yadegaridehkordi 2023). As industries stand at the forefront of environmental impact, the paradigm shifts toward I5.0 emerges as a pivotal opportunity to revolutionize our approach to production and consumption.

This study explores the intersection between technological advancements, sustainable practices, and the imperative for achieving carbon neutrality in the context of I5.0. The evolution of industrial revolution paradigms represents a trajectory marked by an increasing emphasis on integrating technology and sustainability. I5.0 prioritizes the symbiotic relationship between humans and machines beyond mere technological integration. This human-centric approach, as evidenced by studies such as that by (Dhayal et al. 2023a), introduces a novel dimension to sustainable development within industrial contexts. Despite the growing recognition and the potential of I5.0, there is a notable research gap concerning its specific contributions to sustainable development.

The study's significance and problem statement of the present research hold immense potential (Refer to Figure 1). It highlights the industrial environmental impact and also showcases the issues plaguing the industries. It mentions the problems faced by the industries and how the transformative approach of the I5.0 transition can address these challenges. It further emphasizes that achieving carbon neutrality is possible.

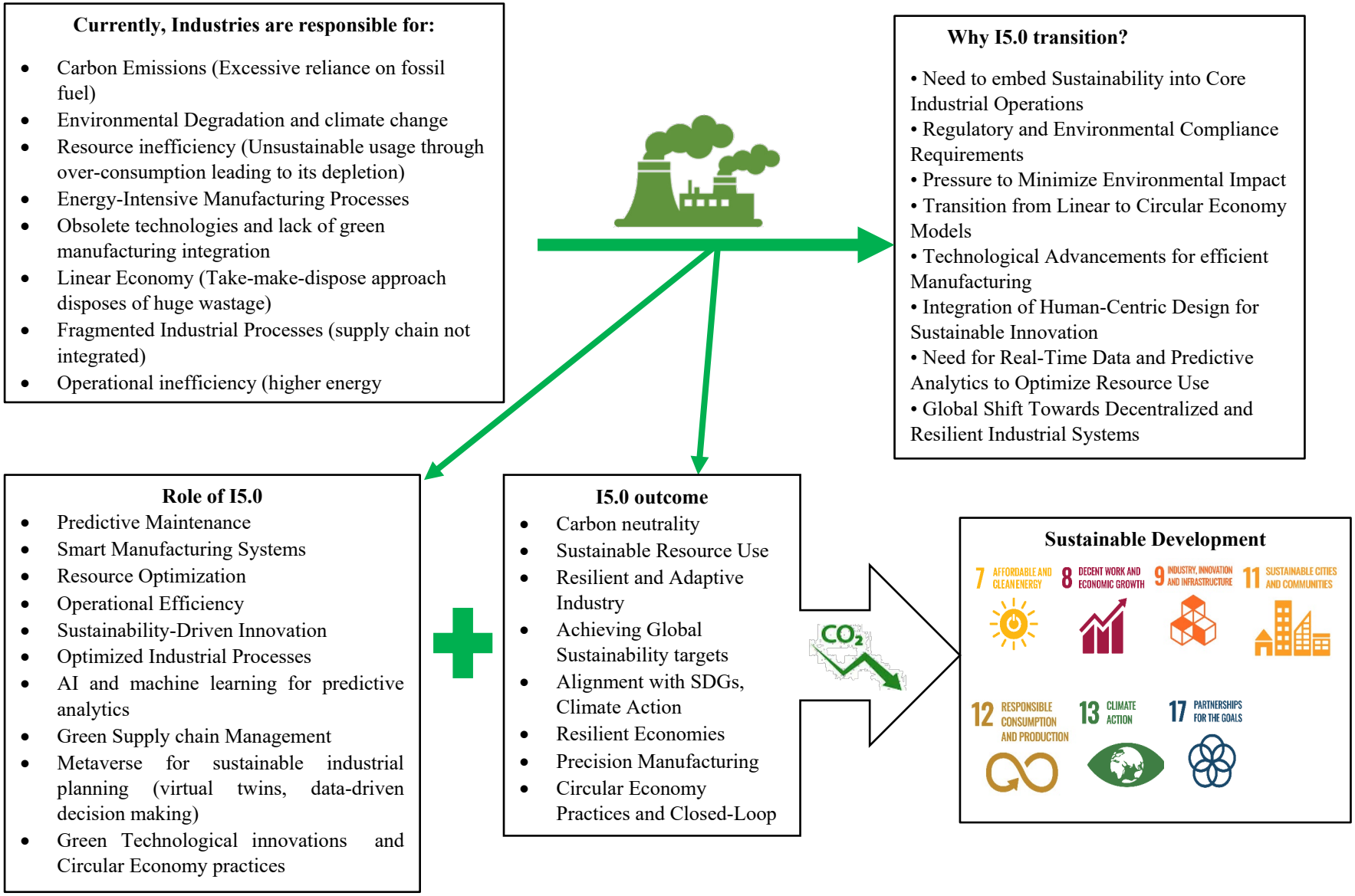


Fig. 1. How I5.0 transition can address the current problems of the Industries (Source: Authors own work)

The introduction of newer technologies has put pressure on increased energy usage. This unprecedented use of energy consumption gives rise to associated problems like energy crisis, high carbon emissions, global warming and many others. Due to this, policymakers have shifted their attention towards energy efficiency (Jafari et al. 2022; Sindhwani et al. 2022; Zizic et al. 2022). Hence, industries worldwide have been accelerating their I5.0 transition pathways to reduce carbon emissions. Awan et al. (2021a) study the big data analytics capabilities, which can help organizations make better decisions towards a circular economy. Furthermore, integrating it with I5.0 can enable more sustainable innovative approaches in the industrial landscape where human-machine collaboration supported by data-driven insights is critical for economic efficiency and fostering sustainability.

1.2 Research Gap and Significance:

The industrial sector contributes almost a quarter of the overall global carbon emissions due to the industrial practices that have dominated since the beginning of the Industrial Revolution (IEA 2021). The transformative shift in industrial practices has become imperative as all nations face climate change challenges. The motivation for the study comes from the need to address the underlying research gap to understand the environmental impact of industrial practices. Since the Industrial Revolution's onset, Industries have been the driver of economic growth and improved technological advancements, but mainly at the cost of environmental degradation (Furstenau *et al.* 2020). The existing industrial practices pollute the environment through high carbon emissions and exploit natural resources, posing a challenge to meeting the targets of the Paris Climate Agreement (Vrchota *et al.* 2020). The study intends to investigate how I5.0 technologies can drive environmental sustainability in existing industrial practices.

There is abundant research discussing the impact of I4.0 on industrial productivity and its environmental impact. Researchers have extensively studied how I4.0 can enhance efficiency through automation, but the overall focus has primarily been on economic benefits rather than environmental impact. However, there is scant literature regarding the intersection of environmental sustainability and I5.0. Global efforts to meet sustainability targets depend upon industrial innovations and the ability to adopt newer technologies to maintain overall economic viability and environmental quality (Yavari and Pilevari 2020; Zizic *et al.* 2022). This research gap exists because, so far, no study has tried to analyze how technological advancements can facilitate the move towards carbon-neutral industrial practices and thus promote environmental sustainability. The present study provides significant critical insights into the potential of I5.0

towards a green and resilient future. This research study is novel as it shows the industry's potential towards economic growth and environmental quality.

Recent technological advancements seek to integrate the principles of I5.0, emphasizing that future progress relies on human and machine collaboration. Now, industries are trying to focus more on *'Planet'* and *'People'* instead of the *'Profit'* (Yavari and Pilevari 2020). The current study offers a holistic overview of the literature on specific I5.0 themes aimed at achieving carbon neutrality, a topic not previously discussed. The study thematically explores a list of enabling cutting-edge technologies and their applications to bridge this scientific gap. The significance of this study lies in its potential to catalyze the transformative change possible through technological advancements within the industrial landscape. As industries worldwide grapple with the escalating challenges of climate change and carbon emissions, this study serves as a beacon of guidance. By elucidating the benefits and challenges of these technologies, the research equips stakeholders with a nuanced understanding of the potential risks and rewards of adopting these technologies. This review study aims to synthesize existing knowledge, elucidate the current state of research, and identify avenues for further exploration. This study answers the following research questions (RQs):

RQ1: What key technological advancements facilitate the transition to Industry 5.0 in pursuing carbon neutrality?

RQ2: How can institutional theories be applied to the emerging technological themes within Industry 5.0 to achieve carbon neutrality effectively?

RQ3: What are the potential benefits, challenges, and future research avenues associated with implementing these technological themes in Industry 5.0?

The remaining study follows the structure as such: Section 2 describes the research framework design and the methodology, and Section 3 deals with the data analysis through performance mapping and network analysis of the corpus of the articles. Section 4 deals with the explanation of the significant thematic clusters. Section 5 deals with the resulting discussion section, while section 6 talks about the implications of the present study by listing out the benefits and the associated challenges of these themes, followed by the future research questions. Section 7 concludes the study and also mentions the limitations.

2. Literature Review:

Industries are significant contributors to environmental degradation due to their high carbon emissions (Tabaa *et al.* 2020). The primary cause of excess carbon emissions is industrialization, which relies heavily on fossil fuel consumption and the linear economy model. Industrial expansion activities increase the environmental footprint and cause pollution, biodiversity loss and climate change. Thus, this degraded environmental quality directly results from traditional industrial practices that often emphasize increased productivity and improved efficiency but at the cost of sustainable development. Hence, the I5.0 transition is not just a technological evolution but represents a much-needed paradigm change demonstrating how industries should interact and operate with the environment (Huang *et al.* 2022).

The global warming limit has been set to 1.5^0 Celsius so that the world can meet its net zero emission targets by 2050 (IPCC 2018). The onset of environmental threat phenomena like global warming, rising sea levels, climate change, heat waves, etc., has made it imperative to decarbonize industries (IPCC 2018; UNEP 2022). The world is finding it hard to ignore the climate-related crisis and is under severe pressure to achieve the global vision of carbon neutrality (IPCC 2023). The environmental impact of industrial practices has become unsustainably profound worldwide, prompting numerous international efforts to mitigate climate change through various agreements. Sustainable industrial progress relies on the responsible integration of cutting-edge technologies with a strong emphasis on environmental stewardship (Akundi *et al.* 2022). However, achieving this vision necessitates coordinated action from all relevant stakeholders, including industries, policymakers, researchers, and the global community. The transition to I5.0 can be accelerated by fostering collaboration across sectors and regions, investing in R&D, and establishing supportive policy frameworks, thereby contributing to a sustainable industrial revolution (Maddikunta *et al.* 2022).

The I5.0 transition is a pivotal shift towards sustainable development using advanced technologies. Climate change necessitates adopting sustainable practices that reconcile industrial growth with environmental sustainability. Also, the Paris Agreement outlines the need for global efforts to reduce the carbon footprint. Thus, the I5.0 transition, along with the integration of technological advancements, happens to be the most promising strategy. The literature on this research domain has increased. Awan et al. (2021b) explore how Internet of Things (IoT) applications can support I5.0 by meeting the continuously evolving expectations of the stakeholders to achieve inclusive circular practices that can benefit society and industry.

Awan et al. (2022) propose future research directions to understand better the interconnectedness of the circular economy, I4.0, and global value chains. Researchers have observed that I5.0 enables personalized production, optimizes global value chains, and enhances circular economy practices, increasing resilience during global challenges.

Also, (Awan & Sroufe 2022) explain the integration of circular economy business models within the purview of sustainability by identifying the obstacles and success factors. Cheng et al. (2021) investigate the impact of technological innovations on carbon emissions to understand the environmental quality of the I4.0 revolution for sustainable growth. Furthermore, post the Covid-19 pandemic era, various challenges have been identified that may hinder the adoption of I5.0 in the supply chain (Karmaker et al. 2023). Rame et al. (2024) identify the innovative practices, technological advancements, emerging trends, and underlying challenges for I5.0 that can help balance environmental sustainability and economic growth. Moreover, Rajesh (2023) attempts to examine the challenges of the manufacturing sector in the I5.0 transition for the developing country. It identifies that regulatory challenges and integration with the existing system are the most critical challenges for adopting I5.0. Ghobakhloo et al. (2022) develop the strategic roadmap for the sustainability-driven I5.0 transition beyond the profit-driven industry 4.0 focus model.

Narkhede et al. (2023) emphasize the potential of integrating advanced technologies into I5.0 for sustainable manufacturing. Sharma & Gupta (2024) explore the case of an emerging economy like India by highlighting the crucial role of I5.0 technologies in aligning global sustainability targets and industrial advancements in the technological innovations landscape. De Giovanni (2023) provides a framework to assess the sustainability of the metaverse through the triple bottom line and the ESG perspective. Baig & Yadegaridehkordi (2023) identify the most common I5.0 technologies as collaborative robots, artificial intelligence, and the Internet of Things. It has conducted a rigorous systematic literature review to offer sustainability practices. Erp et al. (2024) propose a framework for developing the manufacturing strategies in the I5.0 paradigm based on the design and operations (DesOps) methodology that integrates human-centricity, resilience, and sustainability. Dhayal et al. (2024) examine the various innovations and initiatives through which green energy can promote environmental sustainability during the climate crisis.

3. Research Methodology:

In recent years, systematic literature reviews (SLR) as a research methodology have become quite popular due to the rigour in answering the research questions. It makes it easier for the researchers to develop theoretical frameworks, understand areas needing future assistance, explore the evolution of a particular concept and determine the application of a research topic (Agrawal et al., 2022). SLR aims to provide an in-depth analysis of the chosen research field and answers to specific research questions. SLR involves a systematic approach to reducing biases in the search results section of research articles, shortlisting, and summarization. The SLR of any subject field can help comprehensively understand it and provide beneficial information for future research.

Moreover, synthesizing knowledge insights can help develop a different perspective. The present literature review study aims to understand the current state of the I5.0 research domain. The study also uses bibliometric analysis to examine the statistics of published research activity in the field. The bibliometric analysis helps researchers investigate a particular field's evolutionary subject while directing them to emerging study avenues (Chalmeta & Santos 2020). It also aids in understanding collaborative patterns, identifying emerging keywords, and analyzing statistics from published works (Xu et al. 2018). The various stages involved defining the search strategy, followed by the content analysis of the available literature (refer to Fig. 2).

This study adopts a SLR methodology that is comprehensive, transparent, and replicable. By meticulously defining the research design, data collection procedures, and data analysis techniques, the study enables other researchers to reproduce the review process and verify its findings. The selected approach is well-suited for investigating the emerging field of I5.0 and its potential to promote environmental sustainability, thereby making a valuable contribution to the existing knowledge base (Baig and Yadegaridehkordi 2023). The study begins with the research question of how I5.0 technologies can help achieve carbon neutrality by driving environmental sustainability. A systematic and replicable search strategy is crucial to ensure the study is comprehensive and complete. Unlike traditional narrative reviews, the SLR approach follows a predefined protocol that minimizes bias and ensures the review process is comprehensive and replicable (Mourtzis *et al.* 2022). This method is particularly

well-suited for investigating emerging research areas, such as I5.0, where the body of literature is still developing, and there is a need to evaluate the available evidence systematically.

The systematic data collection process entails identifying and selecting relevant studies based on the predefined search strategy and inclusion criteria. This iterative process comprises several essential steps to ensure the comprehensive capture of all pertinent literature. The present study explores the recent academic literature investigating the convergence of advanced technologies and innovations in the I5.0 transition that can promote carbon neutrality. By adopting the SLR methodology, this study can identify gaps in the current literature, integrate findings from diverse sources, and establish a reliable foundation for future research. The transparency and reproducibility of the SLR approach make it a valuable tool for building a coherent and credible evidence base in rapidly evolving fields.

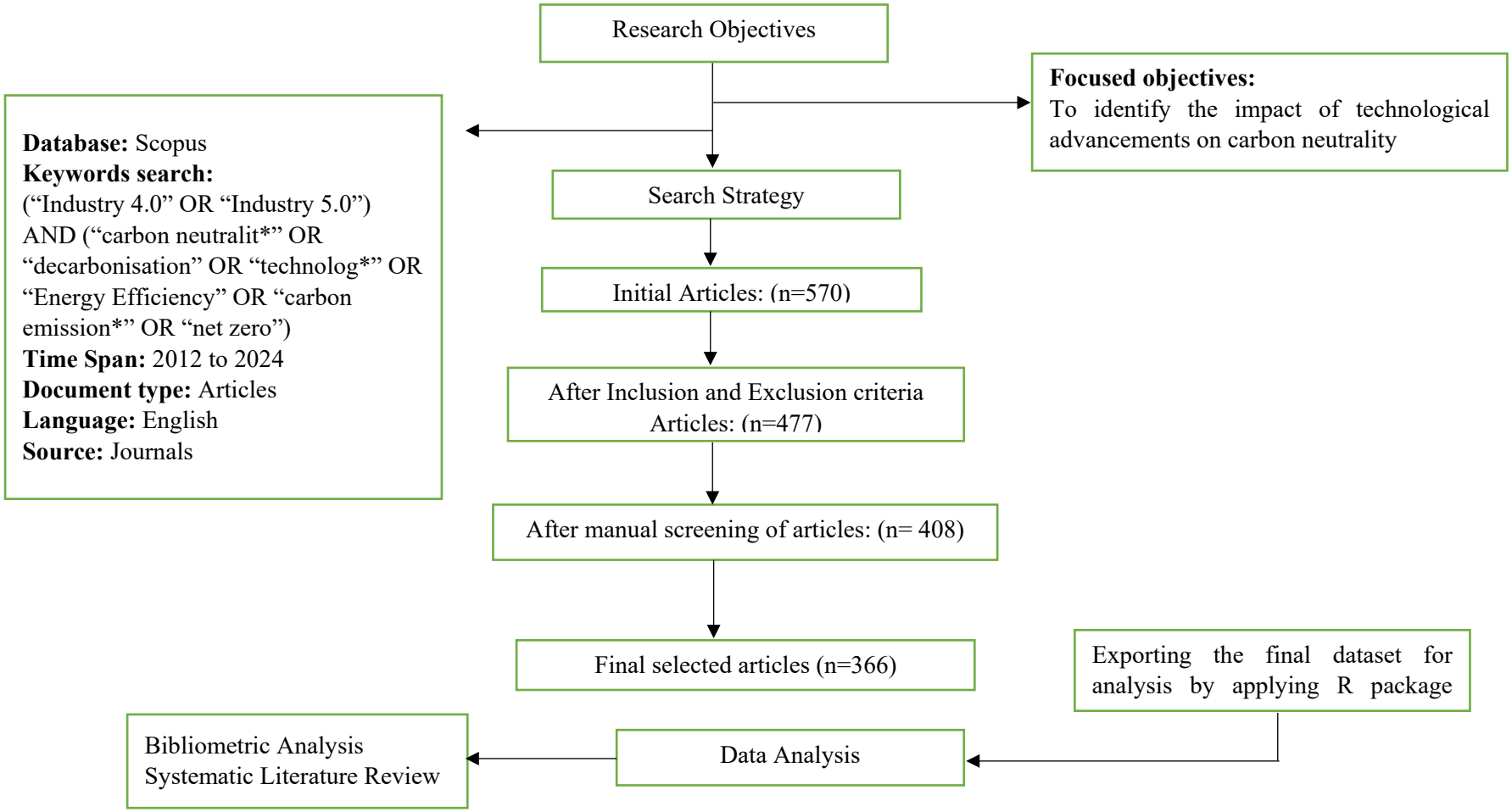


Fig. 2. Research design framework

3.1 Search strategy

The present study implements an extensive search strategy across peer-reviewed articles in the Scopus database. This largest abstract dataset includes peer-reviewed journal citations from well-reputed journals such as Elsevier, Springer, Wiley, Emerald, etc. (Dhayal et al. 2023a). It provides various details about the research articles, such as their citation structure, details of authors, institutes, subject areas, countries and keywords (Raan 2009). Consistent with prior SLR search methodologies, the title, abstract, and keyword fields were searched in the abovementioned database (Han et al. 2019). Keyword searches and forward referencing were performed to identify relevant literature. The keywords search string yielded 570 articles in the Scopus database.

3.2 Inclusion and exclusion criteria

The present study adopts the four criteria to construct the bibliometric information further to enhance the level and depth of the review methodology (refer to Fig. 2). Firstly, it studied the period from 2012 to 2024. Second, the study included only academic research published in peer-reviewed English-language journals to ensure quality and avoid grey literature. Third, the study considered only articles from the final publication stage. Finally, the research study has included theoretical (conceptual and literature reviews) and empirical (quantitative, qualitative, and mixed-method research studies) investigations.

3.3 Screening and selection of articles

After applying the inclusion/exclusion criteria, 477 research publications were identified. Another 69 articles were excluded after thoroughly reading the content of these 477 research articles. Two writers carried out the data extraction and screening process separately, as independent evaluation by two or more reviewers eliminates the chance of subjective bias (Agrawal et al. 2022). Hence, 366 final articles are extracted from the Scopus database to perform the bibliometric analysis and SLR.

3.4 Tools for data analysis

The present study makes use of the VOSviewer and Biblioshiny package software, which are user-friendly software. On the bibliometric dataset, this software provides flexibility and compatibility for performance analysis and scientific mapping (van Eck & Waltman 2010; Derviş 2020).

4. Analysis and findings

4.1 Performance mapping

The existing knowledge on any particular topic can be comprehensively summarized and synthesized through performance analysis. It can help to organize the existing literature through meaningful trend patterns and further identify research gaps. The present study tries to present the data in the form of top meaningfully cited studies and the previous studies of I4.0/I5.0, which have dealt with carbon neutrality. Tables 1 and 2 present the highly cited articles from this corpus and studies that have shown the significance of I4.0/I5.0 solutions for achieving the goal of carbon neutrality.

Table 1. Top cited article(s) from the research domain

Source	Cite	Significance and scope of the study
Siyaev & Jo (2021)	76	Propose mixed reality for embedding the metaverse experience for aircraft maintenance using speech command interactions.
Ng et al. (2021)	19	highlights the need to integrate green finance into the international capital markets to meet the need for ongoing energy sustainability under the I4.0 regime.
Yin & Yu (2022)	96	The study provides a basis for enterprises to carry out their green innovative digital activities.
Umar et al. (2022)	68	It investigates the positive impact of I4.0 technological advancement on the GSCM practices through their economic and environmental performances.
Feng et al. (2022)	39	The notion of green supply chain innovations during the era of I4.0 involves utilizing advanced technologies to tackle environmental issues, such as through sustainable procurement and ecological design methods.
Jiang et al. (2022)	36	studies the negative impact of the I4.0-related IoT technologies carbon emissions on the environment and its correlation with economic growth.
Mourtzis et al. (2022)	35	Integrates metaverse into manufacturing to achieve a personalized society that aims towards a human-centric approach. It further provides a conceptual framework that underlines the opportunities and challenges for the co-existence of I5.0 and S5.0 in the form of a smart intelligent society.
Dwivedi et al. (2023)	17	Identifies the drivers of the I5.0 under the sustainability context for carbon footprint reduction under the paradigm of circular supply chain
Where I4.0: Industry 4.0, I5.0: Industry 5.0, S5.0: Society 5.0		

Table 2. Some select few I4.0/I5.0 previous studies for the carbon neutrality

Author(s)	Significance	Cite
Kurniawan et al. (2022)	Role of smart digital solutions to reform the municipal waste management system and waste recycling industry in St. Petersburg to promote carbon neutrality and finally circular economy	36
Kurniawan et al. (2023)	The study deploys a case-based approach on Malang (Indonesia) to investigate its digitalization-based practices in the waste recycling industry post-pandemic period to promote circular economy in several other urban cities.	26

Yousaf et al. (2023)	The study employed game theory to understand how green technologies can contribute to achieving carbon neutrality in the petroleum industry, aiming to optimize resource circulation within the circular economy framework.	NA
Woon et al. (2023)	It reviews the associated challenges and policy recommendations for attaining "green urban energy development" to curb carbon emissions by minimizing the energy consumption of the urban environment.	11
Javaid et al. (2022)	The literature review study focuses on the role of I4.0 technologies and their associated applications, such as IoT, big data analysis, cloud infrastructure, waste management, smart processes and efficient energy for sustainable manufacturing to preserve the environment.	97
Aheleroff et al. (2022)	The review recognizes the need for sustainability in the mass personalization aspect of I5.0 by proposing the Reference Architecture Model for I5.0 (RAMI 5.0), which is human-centric and more enhanced than I4.0. The study also focuses on the need for Human Capital 5.0, the required competency to achieve cohesion between the pillars of I 5.0.	13
Furstenau et al. (2020)	The study follows the bibliometric approach to determine the performance and network analysis for the research clusters of I4.0 themes and understand their inter-relationship with sustainability, like productivity paradox, flow control, food industry, recycling, decision making, climate change, energy efficiency, circular economy, biofuels, life cycle assessment etc.	160
Hassoun et al. (2022)	This review gives an overview of the green food technologies where I4.0 is finding its presence in areas like extraction, processing, preservation, etc., for transitioning to a sustainable food system. The study emphasizes that these technologies can help reduce food waste, develop healthier food products, implement smart farms, improve food quality, and support food sustainability.	25
Vrchota et al. (2020)	The literature review does the content analysis of the role of green processes (such as product design, logistics, etc.) in sustainable manufacturing for implementing green technological processes in the era of I4.0.	77
Mubarak et al. (2021)	The study deploys the PLS-SEM technique over Malaysian manufacturing firms to investigate how open innovation mediates the green innovation performance towards I4.0 technologies.	55
Sindhwani et al. (2022)	The study integrates technology with human values by identifying various criteria and enablers of I5.0 through the Pythagorean fuzzy AHP approach for attaining sustainability.	68
Present Study	Investigate how the technological advancements will help towards the I5.0 greener transition by attaining carbon neutrality.	NA
Where I4.0: Industry 4.0, I5.0: Industry 5.0, S5.0: Society 5.0		

4.2 Network analysis

Science mapping uses academic publications to understand the dynamic of the knowledge present in that research field. It helps better identify the research clusters, influential studies, and emerging trends to facilitate the intellectual understanding of a particular domain (Donthu *et al.* 2021). Network mapping under the bibliometric approach helps illustrate the scientific dataset's relationship and connections. Network maps use nodes to represent a

particular entity (keywords in this case) and edges to depict their internal connections. Visualization helps to understand the network's structure to recognize the pattern better. Bibliometric analysis helps to analyze quantitative data of scientific publications in a particular research field. The study uses network analysis under the bibliometric approach to help us visualize patterns and relationships and identify trends among scientific publications.

Fig. 3: Word cloud analysis of the top frequently used keywords

Figure 3 depicts the visual representation of the most frequently used keywords in the form of word cloud analysis. It simply emphasizes the frequency of the individual keyword in the dataset corpus by providing a quick overview of the prevalent themes. The size of the keywords in the graphical representation corresponds to their frequency in the publication's dataset. In simple terms, this visualization technique offers an intuitive and concise representation of the significant vital concepts that dominate the literature as they are the most commonly discussed topics. It thus acts as the focal point for comprehending the particular research field through dominant topics to proceed further with in-depth exploration.

Figure 3 illustrates the most frequently used keywords in this research domain. These keywords represent the foundation of this domain and highlight the technological advancements explored by the studies. They are as follows: "Industry 4.0", "Metaverses", "virtual reality", "supply chain management", "industrial revolutions", "environmental management", "green supply chain management", "artificial intelligence", "machine learning", "blockchain", "industry 5.0", "augmented reality", "digital technologies", "supply chain

performance", "cyber-physical system", "internet of things", "human-centric", "generative artificial intelligence", "sustainable development", "virtual worlds", "data analytics", "embedded systems", "deep learning", "health care", "engineering education", "digital storage", and "extended reality".

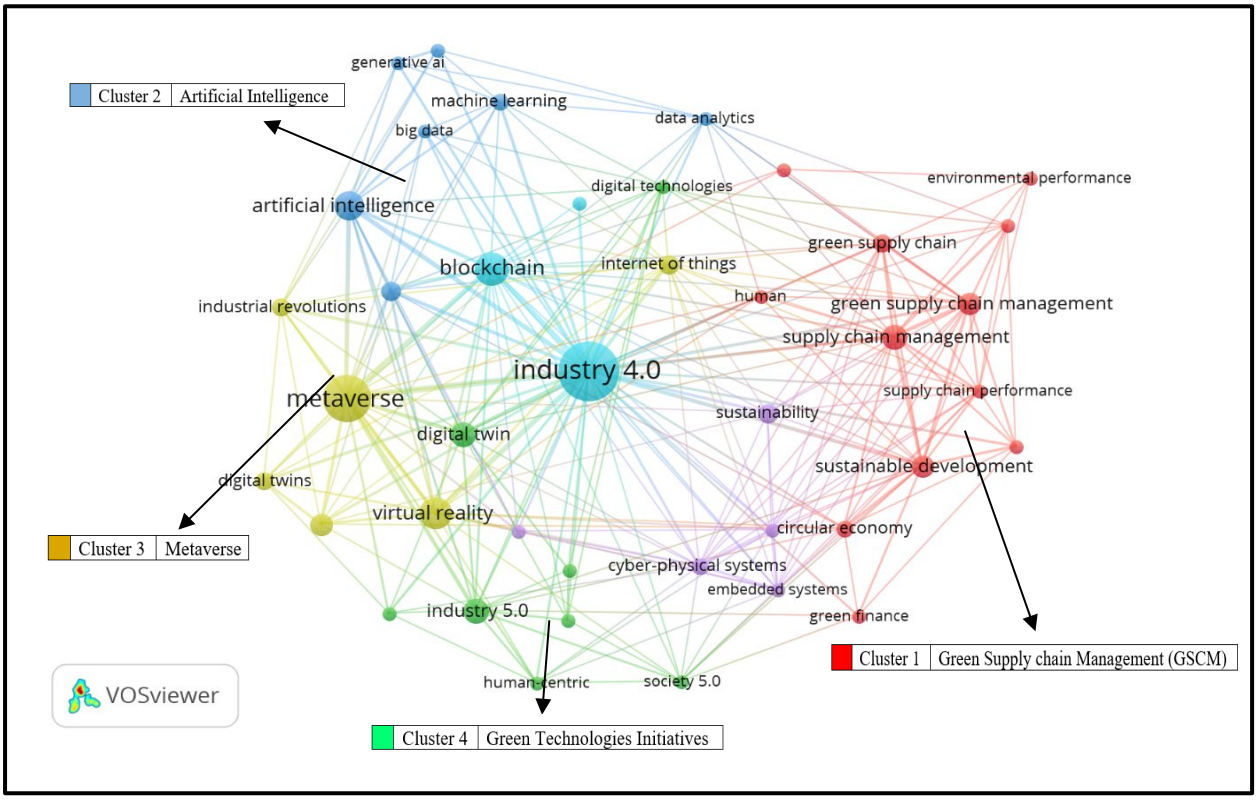


Fig. 4: Keywords co-occurrences

The present study also uses Vosviewer software to explore the thematic relationship. Keyword co-occurrence analysis helps us identify a group or pair of keywords frequently occurring together (Donthu *et al.* 2021). A close look at Figure 4 mentions that the edges indicate the connections between those co-occurrent keywords depicted by the nodes. A close insight into the figure can help decode the thematic clusters and potential future research areas emerging in the particular field. Also, the nodes in the specific cluster represent the same broad theme of the content.

Moreover, specific keywords act as the bridge between different clusters, thereby indicating their interdisciplinary nature. Thus, it facilitates the identification of core topics and their trends. It differs from Figure 4 as it uses the network structure graph to identify the connections between the keywords, while the later gives a quick snapshot of the commonly used terms. Therefore, the research focuses on how data is clustered through these keywords.

5. Thematic clusters

IEA (2021) stressed that governments should support technology innovations to achieve carbon neutrality. *'Technology'* has become a significant factor in production, creating a higher demand for energy use and leading to higher carbon emissions. Various studies (Huang et al. 2022; Kasinathan et al. 2022; Mourtzis et al. 2022) have started emphasizing how the use of disruptive clean technologies should help to realize the goal of society 5.0 (S5.0), which will focus on environmental sustainability as its central aspect. The current section discusses the top four thematic clusters for the research domain. It refers to a group of related topics within the literature. Usually, whenever studies share common knowledge or concepts through interconnected ideas within a particular research domain, it gives rise to research themes.

Thematic clusters are pivotal in SLR and bibliometric analyses by providing a structured framework for organizing and understanding complex research bodies. Bibliometric analysis helps to identify such themes, which is crucial to understanding the body of available knowledge (Donthu *et al.* 2021). These clusters serve as lenses through which researchers can identify patterns, trends, and gaps within the literature, facilitating a deeper comprehension of the subject matter. Researchers can effectively navigate vast literature by categorizing related studies into thematic clusters, enabling sufficient synthesis and analysis. Moreover, thematic clusters aid in the identification of emerging topics, interdisciplinary connections, and areas ripe for further investigation, thus guiding future research agendas (Awan *et al.*, 2021). Mapping these themes helps to explore the research landscape within a particular domain and identify future research directions within that specific field.

5.1 Green Technology Initiatives (GTI)

Green technological initiatives (GTI) play a crucial role in facilitating the transition towards carbon neutrality within the framework of I5.0. GTI focuses on developing and deploying innovative technologies that minimize environmental impact while optimizing operational efficiency. These initiatives encompass diverse solutions, including clean energy systems, energy-efficient manufacturing processes, sustainable materials, and waste reduction technologies (Mehmood et al. 2024). Additionally, GTI leverages digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), and big data analytics to enhance environmental performance across various aspects of industrial operations (Fraga-Lamas et al. 2021). IoT sensors and connected devices enable real-time monitoring of energy consumption, emissions, and other environmental metrics, allowing for proactive management and

optimization. AI and analytics algorithms can analyze considerable data to identify opportunities for energy efficiency improvements and better resource optimization, further reducing carbon emissions. Overall, GTI is crucial to a sustainable and resilient industrial ecosystem for the future.

GTI, such as renewable energy sources, energy-efficient manufacturing equipment, and sustainable materials, will be critical in achieving carbon neutrality. Integrating these technologies into manufacturing processes will lead to a drastic reduction in carbon emissions and environmental impact. Dawe (2012) discussed the green finance aspect a decade back and stressed that there should be a *'Green Industrial Revolution'* which can give rise to *'Green Employment'.* Over time, (Chen et al. 2016; García 2017) talked about deploying green energy to achieve green development. GTI has been continuously gaining traction worldwide as one of the essential tools for achieving a sustainable economy by combating the menace of climate change (He et al. 2021; Mehmood et al. 2024).

The study by Vrchota et al. (2020) proposes that critical technologies, such as big data, smart systems, cyber-physical systems, etc, are crucial for green processes such as smart manufacturing, logistics, and product design. It suggests that the outcomes of this sustainability green industry 4.0 (SGI4.0) will ensure emission reduction, energy savings, resource optimization, efficiency, productivity, economic performance, etc. Also, Bradu et al. (2022) advocate the urgent need to integrate the GTI with IoT technologies for sustainable practices to achieve green recovery for world economies. Through sustainability, GTI brings together innovations that benefit the environment, economy, and society (Ridzuan *et al.*, 2023). For example, industries and manufacturing firms, if funded through GTI projects to encourage the adoption of sustainable practices, then their production process can reduce energy usage and waste generation. Apart from achieving the targets for environmental preservation, it also helps these firms differentiate themselves from their competitors and project themselves as forerunners of sustainability.

Human-centric design principles of I5.0 guide the development of green technologies, ensuring they meet societal needs while minimizing environmental impact (Dhayal et al., 2023b). By fostering innovation and collaboration, GTI empowers industries to adopt cleaner energy sources, optimize processes, and reduce waste. Ultimately, these initiatives drive the I5.0 transition towards carbon neutrality by aligning economic progress with environmental stewardship and societal well-being.

5.1.1 Eco-Innovation theory (EIT): This theoretical framework is essential for identifying how to develop environmentally sustainable products, processes, and models. This theory is critical to understanding how sustainable technologies can support carbon neutrality (Rennings 2000). It states that challenges, such as climate change, often drive innovations and that the resulting sustainable technologies contribute to reducing carbon emissions, improving resource efficiency, and increasing the adoption of renewable energy (Faucheux & Nicolaï 2011). This theory helps identify various barriers and challenges and allows for developing strategies to overcome them by creating sustainable business models that support carbon neutrality. Thus, eco-innovation theory promotes and adopts several cleaner technologies to ensure a smooth I5.0 transition to promote carbon neutrality.

5.2 Metaverse:

The metaverse encompasses a collective virtual realm, emerging from the seamless fusion of digitally augmented physical reality, virtual reality (VR), augmented reality (AR), and the Internet of Things (Tlili et al. 2023). While the metaverse is still in its infancy, its role in I5.0 could be significant in several ways. It allows for virtual prototyping, testing, and refining of energy-efficient manufacturing techniques, thereby reducing carbon emissions associated with traditional trial-and-error methods (Bhattacharya et al. 2023; Mourtzis, Panopoulos, et al. 2022; Siyaev & Jo 2021). By reducing the need for physical travel, the metaverse can lower carbon emissions associated with transportation and energy-intensive manufacturing processes (Siyaev & Jo 2021). Moreover, integrating IoT sensors within the metaverse enables real-time monitoring and controls energy usage, improving production efficiency and supply chain logistics. This data-driven approach empowers companies to identify inefficiencies, optimize resource utilization, and minimize carbon footprints across the entire value chain (Mourtzis et al. 2022).

Through virtual collaboration and remote work enabled by the metaverse, companies can reduce the need for physical travel and office space, lowering carbon emissions. This convergence of technologies fosters innovation, efficiency, and sustainability, positioning the metaverse as a critical enabler of a greener and more sustainable industrial future (Siyaev & Jo 2021). I5.0 aims to make the industrial system more sustainable by ensuring efficient communication between machines and humans. Metaverse can play a crucial role by converging physical and virtual reality (Bhattacharya et al. 2023; Yao et al. 2022). The virtual environment allows industrial operations, processes, and systems to be used for large-scale

training of workers and employees, reducing errors and increasing safety. By leveraging advanced analytics and simulation tools within virtual environments, companies can identify opportunities for energy efficiency improvements and emissions reductions without real-world experimentation, accelerating the transition to carbon neutrality.

Virtual prototyping will allow a platform for the customers to test the products and make personalizations for themselves by reducing the time and, eventually, the cost involved in physical prototyping (Jagatheesaperumal & Rahouti 2022). Tlili et al. (2023) promise of a sustainable society (S5.0), coupled with the rise of implementing the metaverse applications, has become quite promising. The metaverse is set to revolutionize the way businesses operate by offering virtual environments that can simulate real-world scenarios, enabling companies to test and implement sustainable practices without the need for physical resources (Wang et al. 2023). Green metaverse networking has been proposed to optimize energy efficiencies in network components for sustainable development (Zhang et al. 2023).

5.2.1 Technology Acceptance Model (TAM): This theoretical framework can help identify the factors influencing consumers to adopt new technologies and practices supporting carbon-neutral production (Zhong *et al.*, 2021). The two primary factors responsible are namely perceived ease of use and usefulness. In the I5.0 context, many complex technologies will be challenging to adopt, so their implementation will be slow. However, if technologies and practices are designed for end users, their perceived usefulness, adoption, and final impact are higher (Lew et al. 2020). In summary, TAM can help researchers and practitioners design, accelerate, implement, and adopt several user-friendly technologies to expedite the I5.0 transition to achieve carbon neutrality in the industrial sector.

5.3 Green Supply Chain Management (GSCM):

GSCM refers to the integration of environment-friendly practices in the supply chain to minimize their deteriorating impact on the environment across every stage, starting from product design to sourcing of raw materials for manufacturing, transportation, and distribution, followed by the final use of the product and its disposal (Rupa & Saif 2022). Thus, GSCM aims to minimize emissions across the supply chain and reduce waste by adopting sustainable practices like renewable energy, eco-friendly materials, optimizing transportation, etc. (Baz et al. 2022; Feng et al. 2022). GSCM is vital in facilitating the I5.0 transition to carbon neutrality as it optimizes supply chain processes to minimize environmental impact while maintaining or enhancing operational performance (Dhayal et al. 2023b). It involves a variety of approaches

and methods designed to decrease carbon emissions, advocate for resource efficiency, and cultivate a mindset focused on a circular economy (Kumar et al. 2024). One key aspect of GSCM is the adoption of sustainable sourcing practices. It involves selecting suppliers and materials based not only on cost and quality but also on environmental criteria such as carbon footprint, energy efficiency, and use of renewable resources. By collaborating with environmentally conscious suppliers, companies can reduce the carbon intensity of their supply chains.

Another critical component of GSCM is the implementation of green logistics and transportation practices (Dev et al. 2020). By minimizing emissions from transportation activities, companies can reduce the overall carbon footprint of their supply chains (Vrchota et al. 2020). Additionally, GSCM involves implementing waste reduction and recycling initiatives throughout the supply chain. It involves creating products with recyclability in mind, integrating closed-loop manufacturing methods, and collaborating with suppliers to recycle or repurpose materials. By promoting a circular economy mindset, GSCM minimizes waste generation and maximizes the value extracted from resources, further reducing carbon emissions (Rupa & Saif 2022). Furthermore, GSCM leverages digital technologies such as IoT, blockchain, and data analytics to enhance transparency and traceability across the supply chain (Umar et al. 2022). It allows organizations to track and improve their environmental impact in real-time, pinpoint areas for enhancement, and make decisions based on data to decrease carbon emissions.

GSCM allows organizations to monitor and enhance the efficiency of their complete supply chain, from procuring raw materials to delivering final goods to customers. It will result in reduced waste, energy-efficient transportation, and the effective utilization of resources, contributing to a more sustainable production process. GSCM is critical in achieving carbon neutrality in I5.0 by integrating sustainability principles into supply chain management practices (De Giovanni & Cariola 2021). GSCM helps companies minimize their environmental footprint and contribute to a more sustainable future by optimizing supply chain processes, reducing emissions, and promoting resource efficiency.

5.3.1 Theory of Planned Behavior: The I5.0 transition can be better understood from the lens of the Theory of Planned Behavior (TPB), which can help to realize three main factors, namely attitude, subjective norms, and perceived behavioural control, which are responsible for influencing the industries decision to imbibe the new technologies (Ajzen 1985, 1991).

Industries willing to adopt cleaner technologies greatly benefit from energy efficiency and productivity. Industries usually fall under subjective norms pressure at regular intervals of time periods to meet the demands of regulators, customers, and competitor firms. For instance, firms have been following the practice of ESG disclosure to mention, manage and mitigate their risks related to environmental, social and governance criteria. It has also helped them to make concerted efforts to reduce their carbon footprint. These norms influence their decision-making in adopting the recent trend of technologies. Perceived behavioural control reflects how firms react and respond to I5.0 technologies based on their organizational culture and resource availability. In short, TPB offers a framework design which the policymakers can use to nudge the industries through a framework design for influencing the firm's decision. The three factors of TPB can help them develop specific strategies for taking the necessary action to adopt I5.0 technologies. TPB helps identify how various factors influence stakeholders' attitudes towards adopting sustainable technologies and carbon neutrality practices.

5.4 Artificial Intelligence (AI)

Artificial Intelligence has disrupted many industries and continuously brings innovation to every part of our lives (Dwivedi et al. 2023; Jabrane & Bousmah 2021; Panagou et al. 2023; Rožanec et al. 2022). A few studies (Rožanec et al. 2023; Taj & Zaman 2022) have tried to explore how the human-robot interaction can help various industries. This research cluster examines the transformative role of artificial intelligence (AI) and generative AI (GAI), combined with big data analytics and machine learning, in facilitating the I5.0 transition towards carbon neutrality. Industries can significantly reduce carbon emissions while enhancing operational efficiency by harnessing the power of AI-driven predictive maintenance, energy management systems, and supply chain optimization (Fraga-Lamas et al. 2021).

GAI algorithms enable the creation of innovative, sustainable designs and processes, while data analytics provide insights for continuous improvement. Machine learning algorithms empower decision-makers with real-time insights, enabling proactive measures towards sustainability goals (Taj & Zaman 2022). This integrated approach optimizes resource usage and fosters a culture of sustainability across organizations. Various studies (Chander et al. 2022; Özdemir & Hekim 2018; Rožanec et al. 2023; Taj & Zaman 2022) highlight the potential of AI technologies through case studies and simulations in mitigating carbon footprints and shaping a greener future for industrial operations in alignment with global carbon neutrality objectives. Artificial intelligence has made it convenient for the humans to

communicate with the machines. These interactions have grown tremendously over time and will grow exponentially in the upcoming I5.0 transition since I5.0 is a human-machine-centric approach. Therefore, there is a need to explore how generative artificial intelligence (GAI) will shape our future world.

GAI is a technology based on AI algorithms capable of generating content like text, audio, and images (World Economic Forum 2023). GAI can optimize manufacturing processes, reducing energy consumption and waste generation. It can also facilitate the development of innovative and sustainable products by generating new design possibilities that prioritize environmental impact. Sætra (2023) explores the implications of GAI in shaping a future sustainable society. It emphasizes the need to investigate further how this technology can disrupt societal norms at various micro, meso and macro levels. The study by Heo et al. (2022) emphasizes achieving a net zero carbon emissions roadmap using GAI models to demonstrate how energy generation costs and carbon emissions can be reduced. Chien et al. (2023) evaluate the carbon impacts of GAI interference and its associated applications, further highlighting the need for and importance of more technological advancements to mitigate the environmental impact caused by AI.

5.4.1 Disruptive innovation theory (DIT): This theory can help understand how advanced technologies can disrupt traditional business models and manufacturing practices to create products through a green and sustainable production system (Ho 2022). Therefore, such disruptive advanced technologies are one of the enablers for adopting less carbon-intensive innovative products. I5.0 integrates advanced technologies like IoT, robotics, and AI into industrial processes. These transform the entire chain of production system from manufacturing to distribution and finally to consumption. The resulting changes can be seen in the efficient energy consumption, waste minimization, and more usage of renewable energy (Gemici & Alpkan 2015). Moreover, disruptive innovations can help overcome many barriers to the I5.0 transition through economies of scale by making technologies easily affordable and accessible to many businesses. It further helps entrepreneurs and firms leverage the available technologies to address sustainability challenges by improving resource efficiency and building upon carbon neutrality solutions.

6. Discussion

European Commission (2021) report titled *'Industry 5.0: towards a sustainable, human-centric and resilient European Industry'* mentions that the "*New Industrial Revolution*

I5.0" will be human-centric, sustainable and create a carbon-free future world. I5.0 focuses more on the circular mode of production and implementation of innovative cleaner technologies, which can help use natural resources more efficiently. Therefore, the industries will be based on resilience, sustainability and a human-centric approach (Akundi et al. 2022; Xu et al. 2021). The approach is to ensure that humans are integrated with nature through the co-existence of machines. It will revolve around energy-efficient machinery offering low-carbon or carbon neutrality solutions and thus promote sustainable development goals (Ghobakhloo et al. 2022). European Commission (2021) mentions I5.0 as a visionary approach to move further and beyond the existing realms of manufacturing. It complements the existing practices by giving an angle of socio-environmental dimension, which promotes intelligent businesses. Integrating the human touch into the technological aspect encompasses the triple helix sustainability model. Therefore, these emerging technologies facilitate the move towards I5.0 and further ensure the achievement of SDGs.

The four research themes are associated with the ongoing industrial-technological revolution. Under the I5.0 paradigm, the metaverse represents a digital realm where individuals can engage with computer-simulated surroundings. It can be applied to digital twins to better optimize smart factories in the manufacturing process through augmented reality. This human touch is a more central aspect of the I5.0, where the metaverse can facilitate the creation of virtual spaces where humans and machines work together. GSCM uses technologies like data analytics, sensors, IoT, etc., to optimize and digitalize the existing supply chains. Thus, GSCM leverages the technologies for waste reduction, enhancing supply chain efficiency by making them environmentally sustainable. GSCM further aligns with the I5.0 principles as it involves the human workforce in ethical and sustainable practices promoting environmental responsibility.

AI can be applied to optimize the production process, perform predictive maintenance, and create smart products, contributing to the manufacturing system's automation and intelligence. GAI finds it connected with the I5.0 as human-machine collaboration is heightened to find creative ways to solve problems and foster innovations. The GTI, such as efficient manufacturing and renewable energy sources, makes the I5.0 transition more environmentally friendly because industrial processes are now resource-efficient. Under I5.0, these GTI can align the industrial practices with societal values to ensure that the technology is employed to minimize the environmental impact. Furthermore, Table 3 delineates the

benefits, challenges, and future research directions associated with these thematic clusters, providing a comprehensive overview of their significance.

This study has provided a comprehensive overview of I5.0 and its potential to drive sustainability while identifying several areas for future research (refer to Table 3). These include longitudinal investigations into the long-term environmental impact of I5.0 technologies, analyses of policy and regulatory frameworks influencing technology adoption, and examinations of how human-centric approaches in I5.0 affect sustainability outcomes. Also, there is a need to assess the economic viability and scalability of green technologies within I5.0 frameworks and explore how I5.0 technologies can support the implementation of circular economy principles in industrial practices.

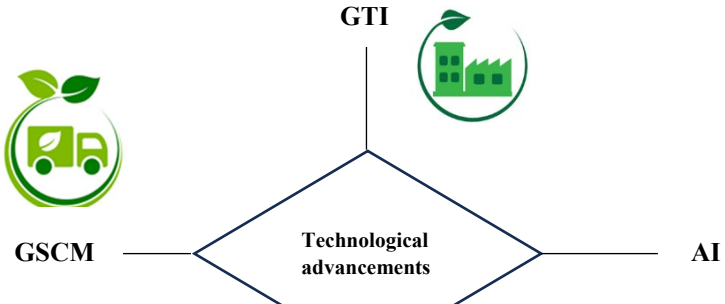
Table 3. Benefits, Challenges and Future Research Directions associated with the research themes

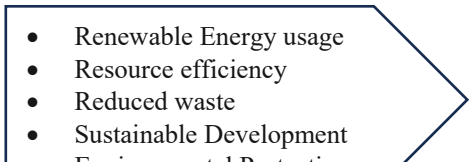
Theme 1. Green Technology Initiatives (GTI)			
Benefits	**Challenges**	**Future Research Directions**	**References**
1. Cost savings on waste management and energy consumption. 2. Green industries differentiate themselves as environmentally responsible. 3. Long-term resilience to climate change. 4. Better access to funds through green bonds, venture capital investments and sustainability-linked loans. 5. Brand building as industries build a positive image among their customers and investors. 6. Enhanced access to newer markets and customer segments. 7. Improved regulatory compliance. 8. Embrace sustainability by addressing societal challenges like the well-being of society, inequality, biodiversity loss, etc 9. Increased supply chain resilience with better operational efficiency. 10. Creates positive impact on local communities by improving health, preventing environmental degradation, etc.	1. Industries do not know how and which GTI can help them in their sustainability initiatives. 2. Too many Green Financial products and services make selecting difficult as there is no standardization. 3. GTI projects involve high upfront costs, a barrier for SME firms. 4. Emerging economies have limited availability of GTI products. 5. Regulatory frameworks are still in the developing stage. 6. Trade-off between managing the goal of financial returns and meeting the sustainability targets.	1. Developing standardized approaches and taxonomies for greasing sustainability impact. 2. Investigate green financing mechanisms involving innovation, such as crowdfunding platforms and blockchain-based financing. 3. Explore ways of stakeholder engagement for better transmission of sustainable practices. 4. Integrate GTI with the I5.0 transition and understand how it can support it. 5. GTI do not yield good returns on their investments, so innovative ways should be identified to maximize their economic impact. 6. Understand how regulators can frame their incentives and develop a uniform framework for the uptake of green, sustainable practices. 7. Identify the enablers and barriers to GTI adoption in I5.0. 8. Analyzing the effectiveness of AI, Big Data, blockchain, IoT, etc., to understand their role in accountability, efficiency and transparency for green practices in the I5.0 transition. 9. Accessing public-private partnerships for achieving sustainability through the I5.0 transition.	(Faruqi 2019; Hu et al. 2022; Ng et al. 2021, 2021; Sindhwani et al. 2022; Dhayal et al. 2023a; 2023b; Ridzuan et al. 2023)

Theme 2. Metaverse			
Benefits	**Challenges**	**Future Research Directions**	**References**
1. Efficient collaboration between humans and machines. 2. Increased safety and reduced errors improve efficiency. 3. Remote working reduces transportation. 4. Reduced environmental impact through less carbon emissions. 5. Real-time data analytics. 6. Industrial innovations. 7. Improved Customer experience.	1. Technical glitches, limitations, and user interfaces cause compatibility issues for various platforms and devices. 2. High cost of deployment of virtual technologies. 3. Privacy and security concerns for data usage. 4. Limited knowledge understanding. 5. Remote workers are isolated and disconnected from the physical world. 6. The digital divide and poor access to technology further exacerbate inequalities. 7. Regulatory, legal and intellectual property rights challenges. 8. Maintenance and updating of the virtual reality system should be done regularly. 9. It isn't easy to replicate the physical environment, process and system in a virtual environment.	1. Explore the role of virtual reality in industrial design and product innovation. 2. Identify the barriers to integration of physical and virtual environments. 3. Investigate the role of AI to enhance virtual reality. 4. What can be new business models of virtual reality? 5. Examine the social implications and issues like equity, inclusion and access. 6. Investigate human behaviour and well-being. 7. Development of interoperability standards and protocols across different platforms and devices. 8. Understanding the ethical and legal implications concerning privacy, responsibility and liability issues. 9. Evaluation of the environmental impact of virtual reality. 10. Explore the role of the metaverse in promoting GSCM practices. 11. Investigate the potential of metaverse for circular economy. 12. Develop tools, designs and products for a virtual reality environment.	(Bhattacharya et al. 2023; Tlili et al. 2023; Yao et al. 2022; Chander et al. 2022; Pereira et al. 2020; Ghobakhloo 2020; Sindhwani et al. 2022; Xu et al. 2018; Jagatheesaperumal & Rahouti 2022; Leng et al. 2022)
Theme 3. Green Supply Chain Management (GSCM)			
Benefits	**Challenges**	**Future Research Directions**	**References**

1. Less environmental impact through reduced carbon emissions and waste generation. 2. Reliance on energy efficiency and resource utilization. 3. Promotes collaboration and accountability amongst the stakeholders. 4. A significant increase in performance was observed at the environmental, financial, and operational levels. 5. Push for innovation through the development of sustainable products and processes.	1. The significant investment cost makes it difficult for SMEs with limited resources. 2. Lack of awareness and understanding of what GSCM can do. 3. Increased resistance amongst the suppliers since they have to change their established processes. 4. Global supply chains with multiple suppliers and complex logistics find adopting GSCM across all stages challenging. 5. Monitoring and reporting are difficult for complex supply chains.	1. The role of emerging technologies like AI, IoT, blockchain, robotics, etc., is to ensure transparency, sustainability, and reporting and monitoring of GSCM practices. 2. How circular economy principles can ensure closed-loop supply chain and resource recovery for GSCM. 3. Investigate the potential collaboration and partnerships amongst the government, industry, civil society organizations, innovators, etc., to promote the GSCM practices. 4. Role of behavioural aspects amongst the stakeholders for GSCM adoption. 5. Establish a framework for the complex supply chain to adopt GSCM practices quickly. 6. Evaluate GSCM practices through life cycle assessment to determine the environmental impact and understand future opportunities. 7. Explore the role of government in bringing policies, regulations, practices and incentives particles for developing countries. 8. Examine sustainable procurement practices such as green purchasing, ethical sourcing, and supplier evaluation.	(Balon 2020; Dhayal et al. 2023a; Fahim & Mahadi 2022; Govindan et al. 2016; Kharola et al. 2022; Rupa & Saif 2022; Umar et al. 2022)
Theme 4. Artificial Intelligence (AI)			
Benefits	**Challenges**	**Future Research Directions**	**References**
1. Intelligent automation of repetitive complex work assignments to reduce errors. 2. Customized manufacturing designs as	1. Job loss and displacement risk as machines will take over human work. 2. Security concerns related to	1. How to address the biases in the generated content. 2. How can the generative models be used in domains with scattered and expensive data to	(Anu & Ansah 2023; Dwivedi et al. 2023; Houde et al. 2020; Jo 2023; Pavlik 2023; Lun et

per the customer needs to reduce waste. 3. Improved decision-making through data insights. 4. Resource optimization can help cut down involved costs and reduce waste generation and sustainability. 5. Operational efficiency. 6. Industrial hazards and accidents can be prevented.	data handling, such as cyber-attacks. 3. Ethical concerns for privacy and massive potential for biased information. 4. A highly skilled workforce is needed to maintain extensive data and complex machinery.	perform semi-supervised learning? 3. What measures can ensure the integration of GAI with other AI techniques like meta-learning and reinforced learning? 4. How can the creativity of the content remain intact, especially for domains where originality matters? 5. Designing manufacturing processes where AI optimizes energy usage. 6. Can AI predict and prevent machine failure and ensure repair warnings for energy-intensive? 7. In what ways can AI support the circular economy development models? 8. Tracking of carbon emissions in the transportation sector, supply chain and other industrial processes. 9. Identifying the AI opportunities for deployment of GF to reduce carbon footprints. 10. How can AI identify the appropriate renewable energy sources for a particular geography.	al. 2018; Fazal et al. 2022; Paschek et al. 2022; Sindhwani et al. 2022)





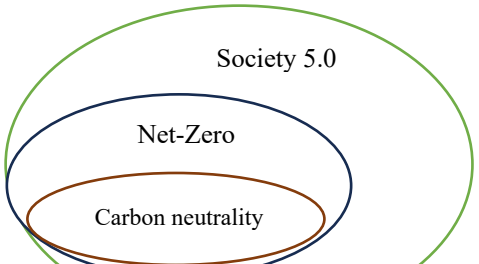


Fig. 5: Proposed framework to achieve Net Zero Economy (**Source:** Authors own work)

7. Contribution of the study

The primary contribution lies in its systematic exploration of how GTI, AI, GSCM, and metaverse can collectively usher in a new era of industrial sustainability (refer to Fig 5). This study provides a nuanced understanding that extends beyond the current literature by listing the benefits, challenges, and future research directions associated with each of these emerging themes. Moreover, the research uniquely addresses the institutional theories underpinning the attainment of carbon neutrality within these research themes. This aspect contributes to the theoretical framework by shedding light on the regulatory and policy frameworks necessary to foster the integration of technologies into sustainable industrial practices. The study offers practical insights for policymakers, industry leaders, and researchers by exploring these themes. It underscores the necessity for carefully calibrated investments in green energy innovation and initiatives, recognizing their pivotal role in shaping a sustainable future. This comprehensive examination of the literature positions the research at the forefront in the field of sustainable industrial practices.

The present study is aligned with global efforts to mitigate climate change and promote sustainable development. Industries and nations worldwide have come together to reduce their carbon footprint by integrating I5.0 technologies into their industrial practices. The study's novelty lies in its interdisciplinary approach that combines various perspectives on the industrial innovations that can drive sustainability. Also, it holds global relevance as the I5.0 transition won't be restricted to a particular region or sector. The benefits of this will spread across the globe to combat climate change. The study also contributes to the discourse on sustainable industrialization as it addresses and aligns with various SDGs. It attempts to provide discourse to sustainable development by developing and deploying innovative technologies for sustainable industrialization (SDG 9) through circular economy principles, which reduce waste and optimize resource use (SDG 12). Moreover, the I5.0 transition allows the integration of green energy across all the industrial processes (SDG 7) and, finally, reducing industrial emissions (SDG 13).

7.1 Theoretical implications

The present study provides an in-depth interrogation of the application of technologies that embed the green transition pathways to achieve carbon neutrality through the I5.0 transition. In the overview of the findings, the study proposes five theoretical implications for the green pathways of future orientation. Firstly, the study's findings will help future researchers comprehend the study's breadth and limitations. Consequently, this study presents

a fundamental and unbiased paradigm for academics, manufacturers, regulators, and policymakers to understand the concept of sustainability in the transition of I5.0 and insight into ongoing research inclination in the domain. Secondly, the research results benefit the academic community and environmental protection advocates by drawing attention to a new and evolving research area essential for promoting the early implementation of circular economy principles and business models to reduce carbon emissions through advanced technologies. Thirdly, it helps to get acquainted with highly referenced articles and relevant prior studies as well as frequently used author keywords in this field of research. Fourth, the cluster analysis findings offer valuable insights into critical foundational works in this research topic and shed light on emerging themes within this domain. Fifth, the proposed areas for future research highlight promising avenues to be explored.

7.2 Practical implications

The research has various important implications for industrial practitioners, stakeholders, policymakers, and environmental protectionists. Industrial practitioners must prioritize the I5.0 transition that will benefit all the concerned shareholders by providing benefits in the form of value addition of the newer technologies while respecting the planetary boundaries and worker's well-being. The government can play a notable role in building innovative strategies such as motivating transition pathways for net zero emissions, promoting energy efficiency and implementing innovative cleaner technologies for more efficient utilization of natural resources. Environmental protectionists focus on GTI as a newer innovation that benefits the environment, economy and society through sustainability. A cumulative effort of academia, government, and industries is needed to establish a resilient and sustainable economy.

7.3 Policy recommendations of the study

Drawing upon the synthesized insights from this research, several policy recommendations emerge as crucial imperatives for navigating the transition toward carbon neutrality in the era of I5.0. Firstly, there is an urgent need for governments and international bodies to establish cohesive, globally coordinated policies that incentivize the integration of green technologies. It includes the development of standardized metrics for assessing the environmental impact of industrial processes and creating regulatory frameworks that encourage investments in sustainable technologies. Additionally, the study underscores the importance of promoting green finance mechanisms. Policymakers should work toward

developing financial structures that encourage investments in environmentally sustainable projects, renewable energy, and green technologies. Furthermore, the study emphasizes the importance of tailored policy approaches for emerging economies. Policymakers in these regions should prioritize investments in green energy innovation initiatives, recognizing the dual imperative of economic growth and environmental stewardship. International collaboration and knowledge-sharing platforms can facilitate the transfer of best practices and technologies to support sustainable development goals in emerging economies. In conclusion, the policy recommendations derived from this study offer a roadmap for governments, international bodies, and industry stakeholders to navigate the complexities of I5.0 and sustainable development. By aligning policies with the identified research gaps and leveraging the transformative potential of emerging technologies, these recommendations aim to catalyze a global shift toward a sustainable and carbon-neutral industrial future.

8. Conclusion:

The current research study explains how technological innovations in the metaverse, AI, GSCM, and GTI, will ensure the greener I5.0 transition towards carbon neutrality and eventually S5.0. The I5.0 transition will focus on the greening of the industry and society as they complement each other. The study also conceptualizes a framework that discusses how integrating these cutting-edge technological advancements and their applications in the respective domains will help achieve climate change mitigation. SLR methodology has thoroughly explored the interconnected role between these themes and their contribution towards the I5.0 transition. These emerging disruptive technologies will facilitate the move towards not only I5.0 but also S5.0 and further ensure the achievement of SDGs. I5.0 will strike the right balance between humans and machines as it is more resilient in adapting to uncertain circumstances. There lies an opportunity for advanced technologies to be integrated into the I5.0 framework to mitigate climate change through their sustainability outcomes. The study fills the existing research gap in the literature by providing insights into the development, deployment and implementation of innovative I5.0 technologies towards the pursuit of carbon neutrality.

9. Limitations:

The limitation of the present study is that it restricts itself to only the Scopus database for the article selection. In future, data extraction can be done from other databases to add more value to this emerging area. Also, in the future, the set of keywords can be modified further to

get the studies as needed. Moreover, researchers can try to diversify their approach by expanding their inclusion search criteria to beyond the journal articles. Also, the study does not encompass all emerging technologies within I5.0, potentially excluding other innovations that could affect carbon neutrality. Identifying research gaps and future directions is inherently subjective and might not encompass all potential avenues for further investigation. In the future, the work in this domain can incorporate econometric methodologies, augmenting the insights gleaned from this review. Using quantitative analyses can establish a more robust underpinning for comprehending the nuances within the research domain. It can facilitate the provision of empirical evidence essential for substantiating the theoretical frameworks delineated from this review, thereby contributing significantly to the progression of knowledge in the field. Finally, this idea can be further linked to several ongoing research themes so that different perspectives can be formed.

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