Received: 12 November 2023 | Revised: 2 April 2024 | Accepted: 3 April 2024
DOI: 10.1002/sd.3009

RESEARCH ARTICLE

Sustainable Development WILEY

Darker side of industry 4.0 and its impact on triple-bottom-line sustainability

Ganesh Narkhede[1] | Vishwas Dohale[2] | Yash Mahajan[3]

[1]Department of Mechanical Engineering, Vishwakarma Institute of Information Technology, Pune, India
[2]DCU Business School, Dublin City University, Ireland
[3]Assembly & Testing, Cummins Turbo Technologies, Charleston, South Carolina, USA

Correspondence
Vishwas Dohale, DCU Business School, Dublin City University, Dublin, Ireland.
Email: dohale.vishwas@gmail.com

Abstract

While the literature commonly prevails a positive outlook on how Industry 4.0 (I4.0) enhances sustainability, there exists an understudied aspect—the darker side of I4.0—that has negative implications and has not yet been systematically addressed. This research aims to challenge the assumption of a sustainable I4.0 by highlighting the potential negative implications of I4.0 technologies on sustainability, emphasising potential measures to mitigate such effects, and presenting a framework for a sustainable future. A dual research methodology was used to conduct this research work. The systematic literature review (SLR) method was used to synthesise the literature. Additionally, a questionnaire was sent to 34 manufacturing Small and Medium-Sized Enterprises (SMEs) to measure their current progress towards triple-bottom-line (TBL) sustainability. This SLR navigates through the complex multifaceted nature of the dark side of I4.0, including job displacement, wage disparity, cybersecurity risks, socio-economic disparities, and environmental effects. This study presents a structured five-step approach that emphasises the integration of cutting-edge I4.0 technologies with a focus on sustainable development practices to address economic, environmental, and social issues for a sustainable I4.0 future. This article aimed to understand I4.0 as a whole phenomenon from the perspective of TBL sustainability. The originality of this research article lies in uncovering the hitherto less-understudied negative aspects of I4.0 and presenting a complex interpretation of I4.0 and its impact on TBL sustainability.

KEYWORDS
industry 4.0, sustainability, sustainable development, sustainable manufacturing, systematic literature review, triple-bottom-line

1 | INTRODUCTION

In the last decade, Industry 4.0 (I4.0) has completely transformed the landscape of the manufacturing sector, offering unprecedented productivity, automation, and connectivity with advanced technologies like the Internet of Things (IoT), Artificial Intelligence (AI), Cyber-Physical Systems (CPS), and Big Data Analytics (BDA) (Ghobakhloo et al., 2021; Li et al., 2017; Rožanec et al., 2022). Within the existing literature concerning I4.0, it is generally recognised that the digitalisation of processes and automation plays an important role in achieving higher efficiency and contributing to economic sustainability (Antony et al., 2023; Beltrami et al., 2021; Ghobakhloo, 2020). Emerging technologies like IoT, BDA, and sensors have the potential to reduce the consumption of resources and energy in manufacturing processes through seamless connectivity and data interpretation which leads to environmental sustainability (Oztemel & Gursev, 2020; Skobelev & Borovik, 2017; Wang et al., 2022). Additionally, some authors Kamble et al. (2018), Müller et al. (2018), and Thoben et al. (2017) concluded that human-machine interface technology contributes to social sustainability and offers benefits, including better working conditions by enabling more ergonomic and safe operations.

This journey of transformation has not been without challenges. Since the rapid adoption of I4.0 technologies has gained momentum, on the other hand, it sparked a spectrum of unintended concerns spanning environmental and social implications, exposing the darker side of I4.0 (Dieste et al., 2023; Dohale et al., 2023). The implementation of I4.0 practices in Indian manufacturing industries has raised concerns about job losses (Narkhede & Chinchanikar, 2024; Pasi et al., 2020). While, environmental issues such as high energy consumption, resource depletion, and electronic waste have been discussed by Moktadir et al. (2018).

Additionally, many organisations prioritise marketing and image-building rather than making serious efforts to promote sustainability (Ruiz-Blanco et al., 2022). This trend is referred to as sustainable washing or greenwashing and is often criticised for undermining and misleading consumers and diluting the impact of genuine sustainability initiatives (Khan et al., 2021). Sustainable washing is the term that describes situations in which organisations promote themselves as sustainable or environmentally friendly without significantly modifying their actual practices (Alonso-Calero et al., 2021).

These challenges underscore the significance of sustainability principles while implementing I4.0 technologies, which aligns with the objectives of sustainable development (SD) goals (Dohale et al., 2024; UN, 2015). SD goals aim to confront Triple-Bottom-Line (TBL) sustainability challenges to ensure a more equitable and environmentally responsible future (Kumar, 2017; Susitha & Nanayakkara, 2023). TBL is an approach that considers three variables of performance: financial, social, and environmental (Alhaddi, 2015). This notion implies that for any organisation to be considered sustainable, it should not only excel financially but also act in a socially responsible manner and minimise its environmental impact (Ahmad et al., 2019). Incorporating the variables derived from intuition or theory is important for several reasons. It helps ensure that the selected variables align with RQs and the underlying theoretical framework. Additionally, it enables comparisons with existing literature and theoretical models, thereby allowing for more meaningful insights derived from the results. Finally, this approach enhances the overall rigour of the study by demonstrating that variable selection was based on reasoned consideration rather than random choice.

The darker side of I4.0, including economic, environmental, and social aspects, presents some critical research gaps. First, studies on I4.0 typically emphasise the positive aspects, but the negative aspects have received less attention and require further in-depth discussion. Second, research on the driving forces and barriers of I4.0 majorly emphasises on economic dimension, while the environmental and the social dimensions have been ignored. Third, there are very few empirical studies conducted on I4.0, and whatever studies are available, the research sample is usually quite small. Fourth, the social implications of I4.0 offer opportunities to regions with labour shortages, like Europe and the USA, while posing challenges for countries like India, where there is a surplus of cheap labour. To the best of our knowledge, very few studies have tried to explore all three dimensions of sustainability from India's perspective. Thus, there is an imperative need to investigate the implications of I4.0 from India's point of view.

In light of apprehensions in the context of the darker side of I4.0, the following three research questions (RQs) are formulated to explore the multifaceted challenges, encompassing socio-economic and environmental implications. The primary objective behind exploring these challenges is to propose TBL sustainable strategies that can attenuate the detrimental effects, thereby paving the way for a future that blends technological innovation and sustainable progress.

RQ1. What unintended consequences can emerge from the implementation of I4.0 technologies?

RQ2. How do the socio-economic and environmental disparities brought by I4.0 contribute to its dark side?

RQ3. What measures can be implemented to ensure that this current transformation is both inclusive and sustainable?

In an attempt to answer these questions and provide a comprehensive understanding of the darker side of I4.0 and its impact on TBL sustainability, this study uses a mixed-methods approach, enabling both quantitative and qualitative data collection. This research is a blend of primary research in the form of a questionnaire survey and semi-structured interview and secondary research through a Systematic Literature Review (SLR) to thoroughly explore the complex and multifaceted landscape of negative aspects of I4.0. Initially, a SLR was carried out to investigate the existing literature concerning the darker side of I4.0. Subsequently, the questionnaire survey approach was used to gain insights into the actual ground reality within manufacturing SMEs located in Pune and the Mumbai region of Maharashtra state, India. The study aims to uncover a more comprehensive understanding of the complex interplay between I4.0 technological advancement and TBL sustainability concerns. This understanding will, in turn, enable stakeholders, policymakers, and industry leaders to devise holistic strategies that capitalise on the benefits of I4.0 while proactively addressing TBL sustainability.

The subsequent sections of this research article are structured as follows: Section 2 describes the methodology used to search pertinent research articles. Section 3 provides a thorough examination of the existing literature. Section 4 delves into a comprehensive discourse on the findings obtained. Ultimately, Section 5 serves as the conclusion, exploring potential directions for future research and acknowledging the limitations.

2 | METHODOLOGY

The research was conducted using a dual methodology approach. Section 3 leverages insights from existing literature through a systematic literature review (SLR) methodology. SLR is an approach used for identifying, assessing, and synthesising all available literature that is pertinent to a particular research question (Xiao & Watson, 2019). It entails an organised and thorough search of scholarly databases, succeeded by a stringent screening procedure to identify pertinent research according to predefined criteria (Dohale et al., 2022; Snyder, 2019). A comprehensive overview of the current state of research on the topic is then provided by critically evaluating and synthesising the articles that have been selected.

Figure 1 shows a rigorous and structured approach to collecting, summarising, and synthesising existing research on the darker side of I4.0. SLR was conducted in the following seven stages, including deciding the research objective (RO) and Research Questions (RQs), finalising

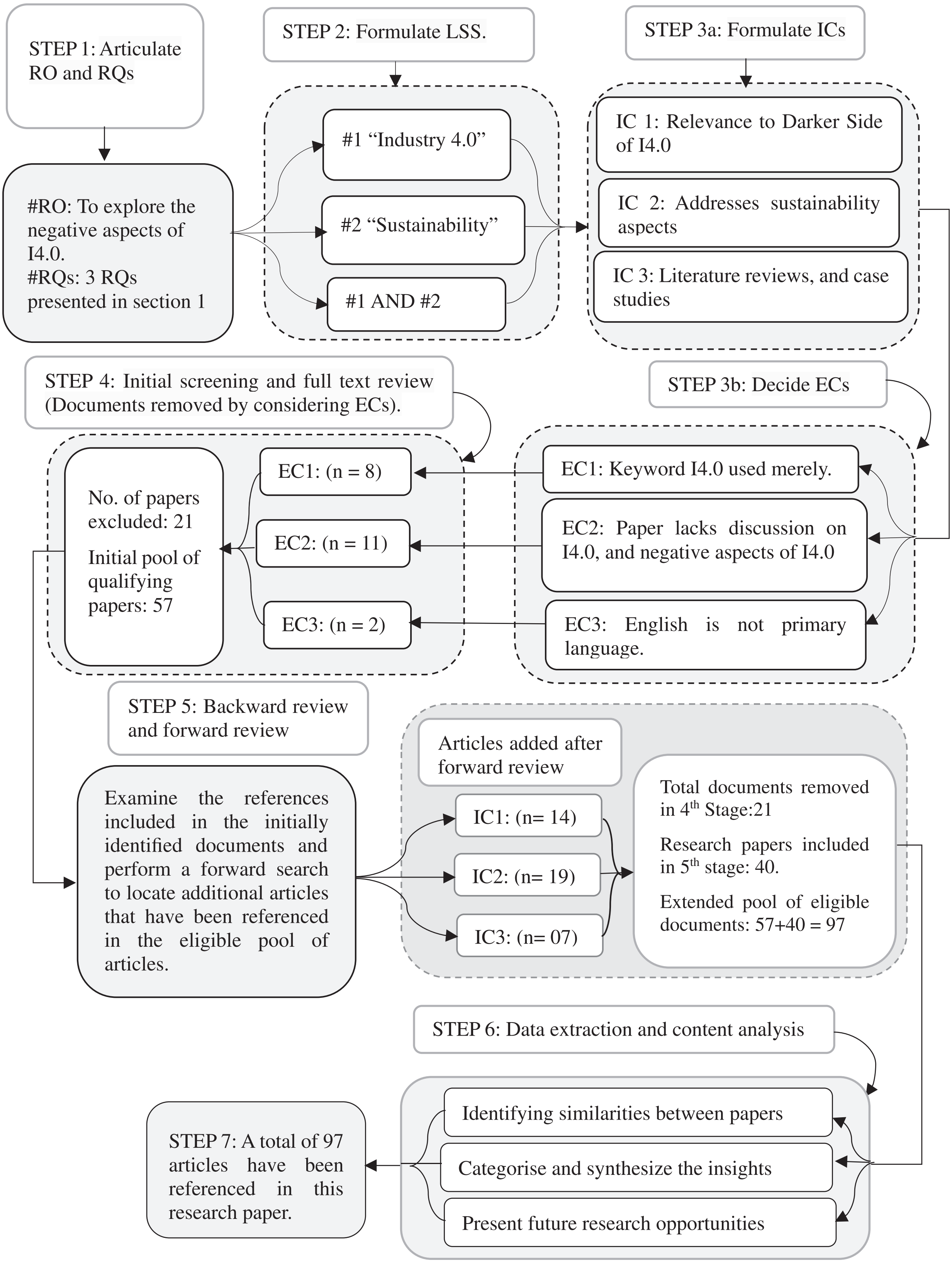

FIGURE 1 Research articles search methodology. (* Source: Author's own work).

Literature Search Strings (LSS), Inclusion Criteria (ICs) and Exclusion Criteria (ECs), initial screening and full-text review, backward review-forward review, data extraction and content analysis, and finally, the results of the SLR are reported in a structured manner in this research article.

The articles were initially retrieved from various databases, including Scopus, Web of Science, Research Gate, and Google Scholar, using LSS and Boolean syntax (AND/OR) as shown in Step 2. Subsequently, the application of exclusion criteria resulted in the exclusion of 21 articles. Furthermore, the number of eligible papers decreased to 33 after an initial screening and thorough review of full-text articles. In the fifth step, the authors reviewed the references cited within the eligible documents and conducted a forward search to find new research papers that had been referenced in the initially identified eligible articles. After forward review, the expanded pool of eligible research papers numbered 65. Finally, the included papers were analysed to categorise them based on their theoretical viewpoints and empirical findings. This categorisation facilitated the accurate reporting and citation of these articles throughout the research paper.

Following this, Section 4 describes a questionnaire survey conducted to understand the current status of I4.0 in Indian manufacturing firms and their implications on social and environmental dimensions.

3 | SYSTEMATIC LITERATURE REVIEW

I4.0 is characterised by the integration of digital technologies, including IoT, AI, and BDA, and has garnered significant attention for its potential to revolutionise manufacturing and production processes (Dionisio et al., 2024). However, this technological transformation is not without its dark side, but literature has mostly illuminated the positive dimensions of I4.0. This research study provides an overview of the emerging issues associated with I4.0 implementation and its impact on the economic, social, and environmental dimensions of TBL sustainability.

3.1 | I4.0: An overview

The pursuit of cutting-edge technologies has always remained a powerful driving force for global changes. The manufacturing sector has always stood at the center of such endeavours, eager to pioneer new ideas and embrace the newer technological frontiers for sustainable manufacturing (SM). It is within this context of industrial revolutions, spanning from the inception of Industry 1.0 to this current fourth revolution, I4.0. Figure 2 depicts these industrial revolutions in chronological order.

I4.0 embodies a transformative paradigm within the manufacturing sector, marked by the seamless integration of digital technologies, automation, and data exchange (Thoben et al., 2017). This evolution is characterised by the adoption of cutting-edge technologies such as IoT, AIML, BDA, CPS, Industrial Robots and Automation (IRA), Augmented reality (AR) and virtual reality (VR), blockchain, and AM (Narkhede et al., 2023; Nascimento et al., 2019).

Table 1 provides an overview of the most widely used I4.0 technologies and their applications.

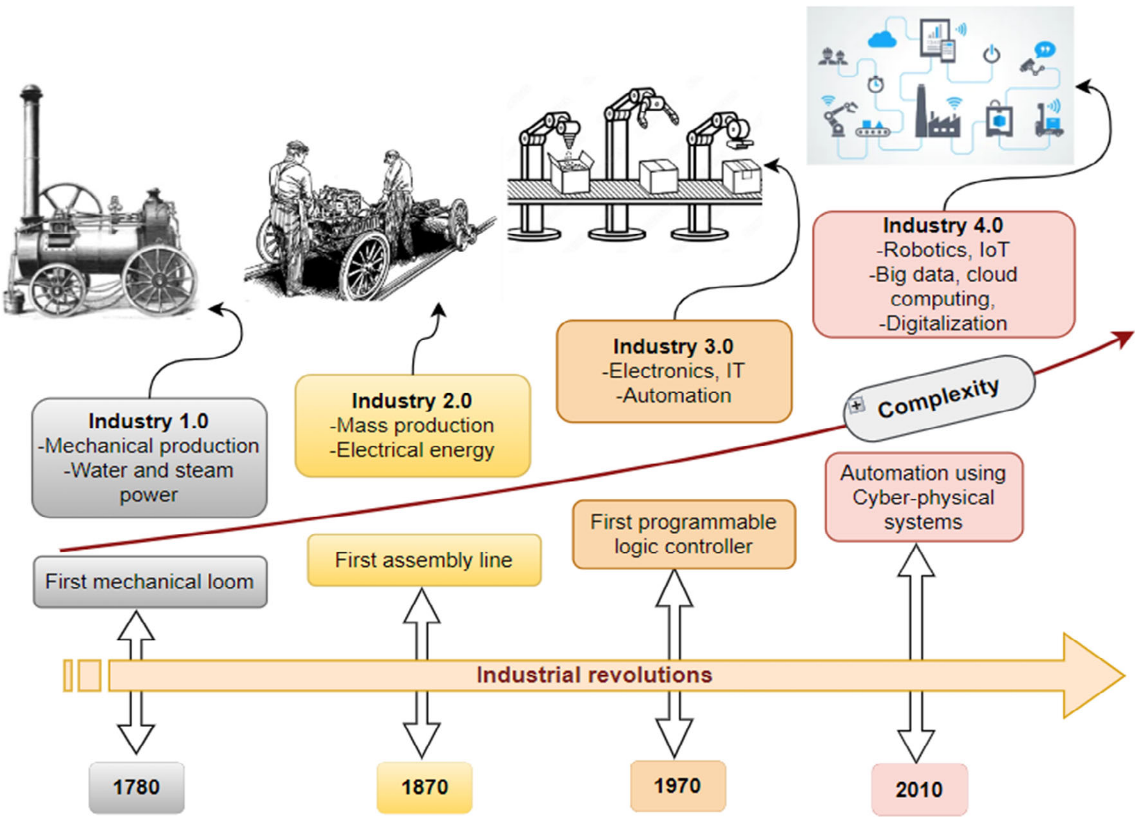

FIGURE 2 Evolution of Industrial Revolutions. (* Source: Author's own work).

TABLE 1 I4.0 technologies and their applications.

Author/s	I4.0 technologies	Applications
Atzori et al. (2010), Oztemel and Gursev (2020), and Trappey et al. (2016)	IoT	Connects machines to the internet, enabling smarter interactions
Kok et al. (2009), Maddikunta et al. (2022), and Monostori (2003)	AIML	Integrates human intelligence in machines to perform work functions autonomously
Buhl et al. (2013), Fosso Wamba et al. (2015), and Vera-Baquero et al. (2014)	BDA	Enables data-driven decisions, and uncovers trends and patterns
Al-Salman and Salih (2019) and Lee et al. (2015)	CPS	Interconnect devices to integrate the physical world with digital intelligence
Aghimien et al. (2020) and Ribeiro et al. (2021)	IRA	To perform hazardous and repetitive tasks to enhance productivity
Durão et al. (2017) and Ramya and Vanapalli (2016)	AM	Rapid prototyping, customisation, and cost-effective production of complex designs
Ghobakhloo (2020), Khanfar et al. (2020), Queiroz et al. (2020), and Zheng et al. (2021)	Blockchain	Creates a distributed and tamperproof digital ledger of transactions
Bednar and Welch (2020) and Nunes et al. (2017)	AR and VR	Embed virtual objects to coexist and interact in the real environment

Source: Author's own work.

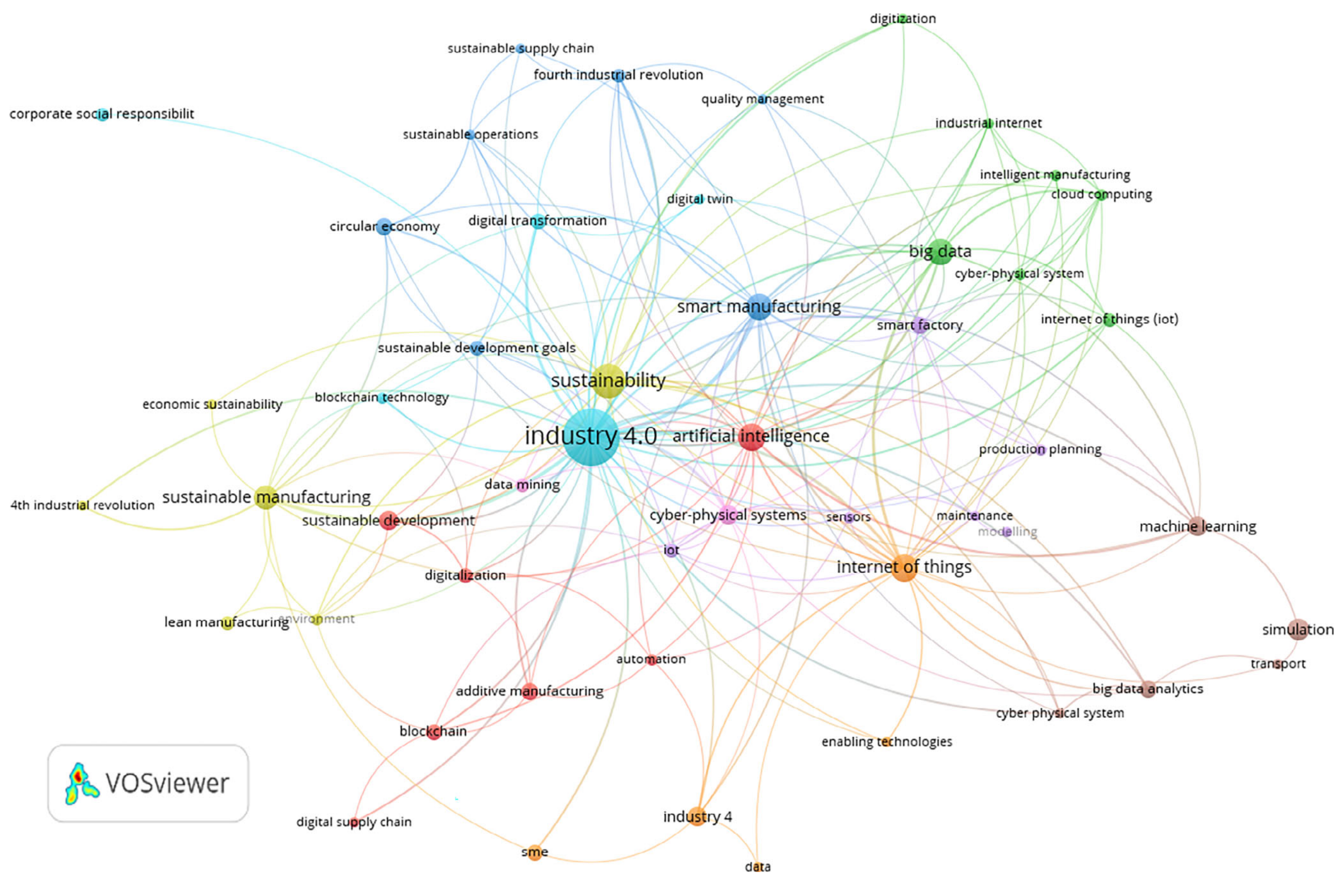

FIGURE 3 Most extensively studied I4.0 technologies. (* Source: Author's own work).

Furthermore, an in-depth bibliographic analysis was conducted with the VOSviewer tool to pinpoint the most extensively studied I4.0 technologies, as depicted in Figure 3.

Through a detailed assessment of existing literature and a comprehensive bibliographic analysis, the authors have pinpointed the most widely used I4.0 technologies and their applications for SM in Figure 4.

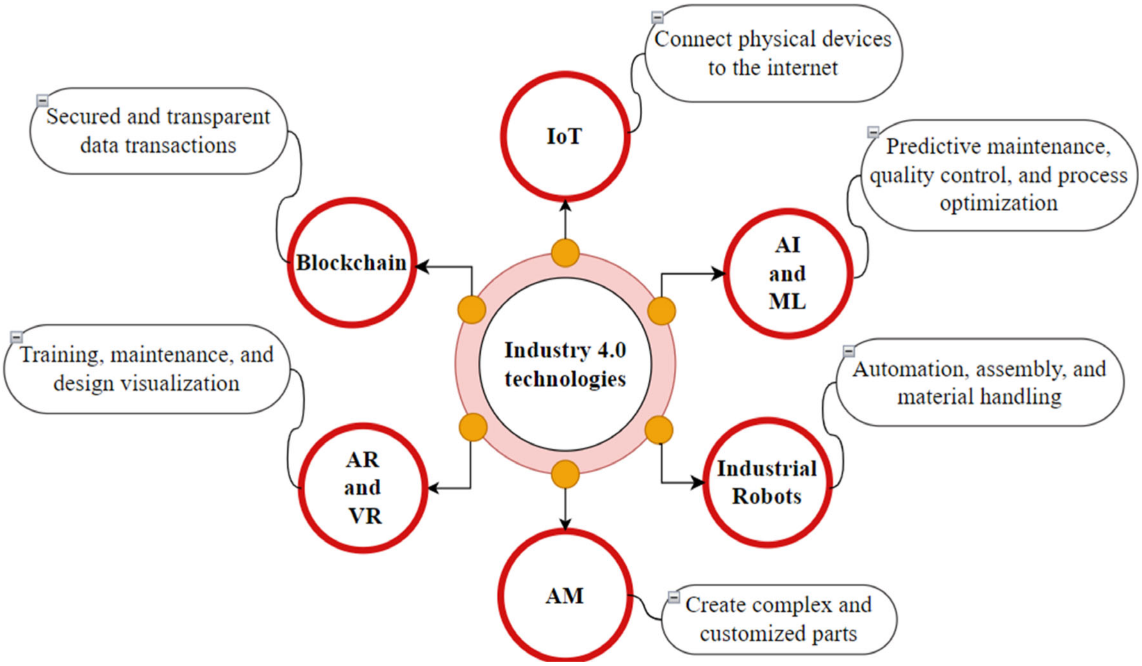

FIGURE 4 Most widely used I4.0 technologies. (* Source: Author's own work).

In line with sustainability principles, SM can be described as the 'manufacturing of products through the processes that minimise negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers, and are economically sound' (Veleva & Ellenbecker, 2001). Although the positive side of I4.0 technologies from the SM perspective is adequately addressed, the less explored and potentially darker side has not received as much attention. Therefore, the following section aims to investigate the negative impact on TBL sustainability.

3.2 | TBL sustainability

The emergence of this multifaceted concept of sustainability has its roots dating back over a century. Still, it gained widespread recognition when the term 'Sustainable Development' (SD) was introduced three decades ago (Ahmad et al., 2019). SD can be referred to as the pursuit of developments that fulfil the present demands without compromising the ability of future generations to satisfy their requirements (Chichilnisky, 1997). Over time, sustainability has evolved to incorporate the pursuit of a balance between economic, social, and environmental dimensions (Alhaddi, 2015). TBL sustainability is a framework that evaluates organisations based on these three interconnected dimensions (Gimenez et al., 2012). Figure 5 shows the concept of TBL sustainability.

Economic sustainability is typically analysed through manufacturing costs or profits (Cruz & Wakolbinger, 2008). However, understanding environmental and social sustainability remained under-explored (Gimenez et al., 2012). In the context of I4.0, the environmental aspect is often referred to as minimising waste, enhancing energy efficiency, lowering emissions, and reducing the use of hazardous or toxic materials (Goodland, 1995). While the social aspect refers to the way the transformation of industries impacts society, the workforce, and broader social systems, and it includes dimensions like workforce impact, inclusivity, digital divide, and privacy (Hami et al., 2015; Sartal et al., 2020).

TBL sustainability refers to a framework for managing and evaluating business performance and its impact on economic, environmental, and social dimensions of sustainability (Gimenez et al., 2012). With the balance among these aspects, manufacturing industries can strive for long-term sustainability while contributing positively to society and the planet (Bednar & Welch, 2020). TBL sustainability promotes responsible manufacturing practices that prioritise social well-being, profitability, and the protection of our environment, aiming for a balanced coexistence of economic growth, social equity, and environmental stewardship (Beltrami et al., 2021).

The existing literature implies that I4.0 significantly increases industrial productivity and positively impacts economic growth (Dieste et al., 2023; Elvis Hozdić, 2015; Margherita & Braccini, 2020). However, it also adversely affects both social and environmental aspects of sustainability (Narkhede et al., 2023; Pasi et al., 2020). Therefore, the following subsections aim to examine the unintended economic, social, and environmental implications of I4.0 technologies.

3.2.1 | Economic dimensions

Although I4.0 has significant positive implications, the darker side of I4.0 poses significant challenges to manufacturing organisations, particularly Small and Medium-Sized enterprises (SMEs). One of the major hurdles is the substantial initial investment required to

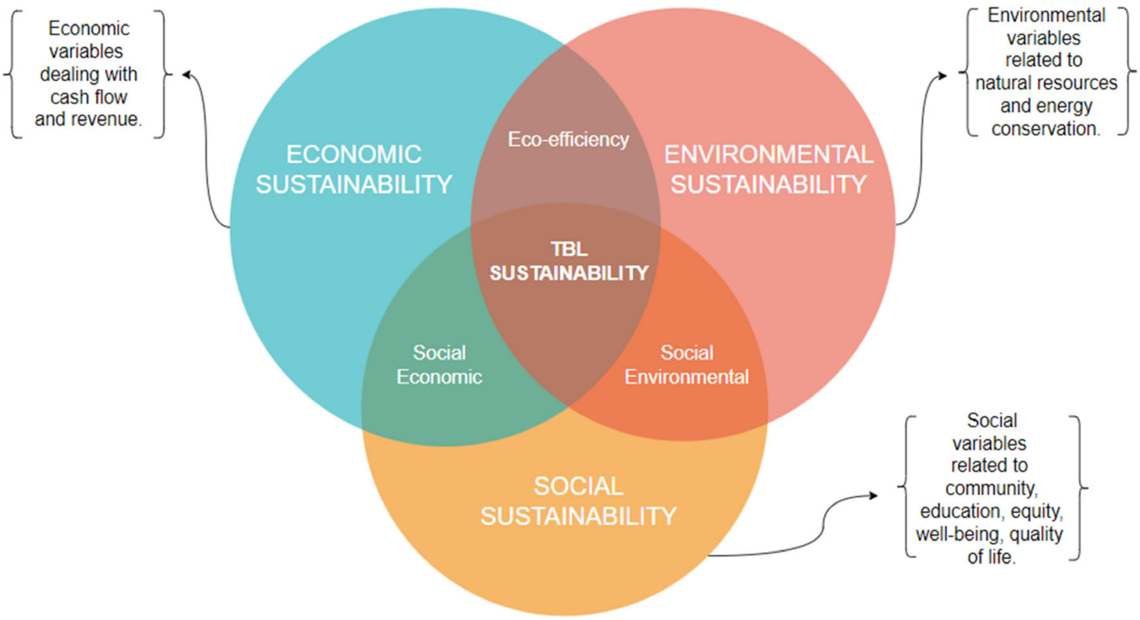

FIGURE 5 Concept of TBL sustainability. (* Source: Author's own work).

implement I4.0 technologies, which hinders the ability of SMEs to compete on an equal footing (Narkhede et al., 2023). This gap in technology adoption extends the economic disparity even further, exacerbating inequality within large enterprises and SMEs (Stentoft et al., 2021). Furthermore, the widespread connectivity of I4.0 enabling technologies has its own set of issues, notably in the context of cybersecurity (Khan et al., 2023). In order to protect their operations from cyber threats, enterprises need to spend a significant amount of resources on cybersecurity measures, significantly increasing operating costs. As a result, it increases the burden on the economic viability of manufacturers, particularly those working with limited funds. I4.0 also adds significant complexity to supply chains, increasing their susceptibility to disruptions. The over-reliance on I4.0 technologies increases the risk associated with supply chain disruptions, potentially leading to significant financial losses.

3.2.2 | Environmental dimensions

In the context of socio-environmental implications, Beltrami et al. (2021) and Ghobakhloo et al. (2021) highlighted an overall excessive optimism of I4.0. The implementation of digital technology can yield both favourable and unintended consequences, potentially leading to the creation of additional sustainable value or diminishing the existing sustainable value (Bohnsack et al., 2021). The widespread application of industrial automation and digital technologies often leads to additional energy requirements to power the increased number of devices and machinery (de Sousa Jabbour et al., 2018). It underlines the significance of undertaking an in-depth examination of the environmental challenges that emerged as a result of the significant rise in energy consumption caused by the adoption of I4.0 (Chiarini, 2021).

AM also consumes more energy due to several reasons. First, the layer-by-layer process used in AM is particularly slow, especially when dealing with larger or more complex components, leading to higher energy consumption. Second, some AM processes require heating materials to high temperatures, which can result in significant energy consumption (Hopkins et al., 2021). The accountability for excessive energy consumption resulting from the proliferation of data centers has also been a subject of concern (Böckin & Tillman, 2019; Müller & Voigt, 2018). This excess energy requirement is being fulfilled from fossil fuels, adding to greenhouse gas emissions and climate change. The significance of SM, particularly with a strong focus on the environmental aspects of sustainability, has been underscored in recent research studies (Heidrich & Tiwary, 2013; Sharma et al., 2020; Sidhu et al., 2022). The fast development of technological advancements leads to shorter product lifecycles and equipment and devices becoming obsolete (Nascimento et al., 2019; J. N. Ribeiro et al., 2022; Souza et al., 2022). This results in electronic waste, which usually is not recycled or disposed of properly, causing environmental hazards due to the toxic parts of electronic equipment.

The production of digital components requires the extraction of rare earth metals and other natural resources (Dieste et al., 2023; Oláh et al., 2020). The production of sensors, semiconductors, and networking infrastructure has shown a significant rise in the consumption of natural resources (Birkel et al., 2019; Chiarini, 2021). This can lead to resource depletion and ecological damage over time, particularly if the resources are taken from environmentally sensitive locations.

With the aforementioned environmental dimensions, balancing the pursuit of efficiency gains with environmental sustainability remains a vital aspect of I4.0's impact on the environment.

TABLE 2 Codes assigned to various unintended impacts on different dimensions of sustainability.

Code	Impact on economic sustainability	Code	Impact on environmental sustainability	Code	Impact on social sustainability
EC1	Initial investment	EN1	Higher levels of energy consumption	S1	Employment
EC2	Cybersecurity threats	EN2	Obsolescence and material waste	S2	Privacy
EC3	Over-reliance on I4.0 technologies can cause supply chain disruptions	EN3	Electronic waste	S3	Unhealthy work-life balance
		EN4	Higher consumption of natural resources	S4	Health and Safety problems

Source: Author's own work.

3.2.3 | Social dimensions

A critical analysis of the unforeseen adverse implications of I4.0, with a specific focus on social issues, has been underscored by (Schneider & Kokshagina, 2021). Their research focuses on the decline of jobs driven by the widespread implementation of new digital technologies and the challenges that arise in managing their work-life balance. In the realm of future production systems, some manufacturing processes are expected to simplify, while a few others are likely to become considerably integrated and complex. As a result, it is anticipated that there will be a surge in the demand for highly skilled employment and a decline in low-skilled jobs (Horváth & Szabó, 2019). Additionally, the implementation of the I4.0 technologies is creating job loss fear among workers in the Indian manufacturing sector (Pasi et al., 2020). The transition towards digital technologies will create a significant skills gap, leaving some workers unsuited for the changing market conditions and restricting economic growth (Horváth & Szabó, 2019). According to a study conducted by Oxford Economics, in Germany, the United States, Japan, and the United Kingdom, automation will take over 41%, 35%, 26%, and 24% of construction jobs, respectively, by 2030 (Grybauskas et al., 2022). This study also revealed that this trend extends beyond the construction sector, and robots can wipe out 20 million manufacturing jobs worldwide by 2030. On a scarier note, the use of industrial robots results in the displacement of 3–6 jobs per robot (Acemoglu & Restrepo, 2018).

Furthermore, in the context of India, I4.0 gives rise to complex social implications (Goswami & Daultani, 2022). In contrast to populated countries like the USA or other European countries, where I4.0 technologies spur positive implications, India faces distinct challenges. Foremost important among these challenges is the potential threat of negative impact on employment, especially in the labour-intensive manufacturing sector (Pasi et al., 2020). This results in exacerbating the existing socio-economic disparities in India. The advent of I4.0 and its digital transformation is expected to create new job opportunities better suited to this evolving digital landscape; however, it may also impact low-skilled or unskilled labour and pose social implications, especially in highly populated countries like India (Dutta et al., 2020).

In view of this social implication, the feasibility of complete human automation remains doubtful. Ethical, privacy, and autonomy concerns pertaining to data sharing in cloud computing also need to be addressed within the framework of I4.0 (Bai et al., 2020). In order to examine the multifaceted circumstances of TBL sustainability, unique codes have been assigned to various unintended impacts that influence sustainability dimensions, as shown in Table 2.

These codes act as concise markers and facilitate categorisation and in-depth analysis of the existing literature addressing different negative impacts of I4.0 on TBL sustainability, as presented in Table 3.

These issues underscore the importance of comprehensive strategies that address TBL sustainability as a whole, ensuring that the benefits of advances in technology are inclusive and sustainable for enterprises of all sizes.

4 | QUESTIONNAIRE SURVEY AND SEMI-STRUCTURED INTERVIEWS

Primary data was collected through a structured questionnaire to gain insights into the current state of I4.0 implementation and its impact on economic, environmental, and social dimensions. The questionnaire covered important facets of the industrial landscape, starting with basic details like the type of industry and sector. Participants were questioned about their acquaintance with the concept of I4.0 and whether they have implemented any of the I4.0 technologies in their operations. A key focus of the questionnaire was to assess the impact of the widespread implementation of I4.0 on the economic, environmental, and social dimensions of sustainability. Participants were asked about the implications of I4.0, including high implementation costs, job displacement, cybersecurity threats, high energy consumption, and excessive use of natural resources due to overreliance on digital technologies and automation. Finally, respondents were asked open-ended questions to provide additional comments and insights about I4.0 and its implications for their respective companies. This carefully crafted questionnaire aimed to capture the ground reality underlying the implications posed by I4.0 for TBL sustainability and to explore the darker side of I4.0 for providing valuable insights for the research study. This questionnaire was circulated to 34 manufacturing SMEs in the Pune and Mumbai regions. Among these, 6 enterprises were classified as micro-sized, 13 as small-sized, 9 as medium-sized, and 6 as large-scale, as shown in Figure 6. In order to obtain a comprehensive picture of I4.0 adoption in Indian SMEs, the sample was

TABLE 3 Unintended impacts on different dimensions of sustainability.

Author(s)	Research domain	Methodology	Unintended impacts on different dimensions of sustainability									
			EC1	EC2	EC3	EN1	EN2	EN3	EN4	S1	S2	S3
Dieste et al. (2023)	TBL sustainability	Delphi method	√			√		√		√		
Pegoraro et al. (2022)	Industrial policy, global value chain	Case study approach									√	
Hariyani and Mishra (2022)	Agile manufacturing	LR	√				√	√	√	√		√
Grigore et al. (2021)	I4.0, corporate social responsibility; digital technologies	Expert interviews								√	√	
Ghobakhloo et al. (2021)	I4.0 and sustainable development	LR	√			√	√			√		
Beltrami et al. (2021)	I4.0 and sustainability	LR				√		√	√	√		√
Rodriguez et al. (2021)	Wireless system integration into I4.0	Experiment	√		√							√
Zhang et al. (2021)	I4.0, internet of things	Survey		√						√		√
Bohnsack et al. (2021)	I4.0 and environmental aspects	LR				√	√					
Chiarini (2021)	I4.0, cyber technology, smart factory environmental implications,	Mixed approach: Qualitative and quantitative		√		√		√				
Cirillo et al. (2021)	I4.0, technological paradigms, organisational change, lean systems.	Case study approach								√	√	
Culot et al. (2020)	I4.0, value chain, customisation	Delphi method	√	√								
(Bai et al. (2020)	Disruptive intelligence and information technologies	Secondary data analysis			√	√					√	
Pasi et al. (2020)	I4.0, sustainability	LR and semi-structured interview	√				√		√	√	√	
Birkel et al. (2019)	I4.0, SMEs, Supply chain management, risk management	LR and expert interviews	√		√	√	√		√	√		
Coldwell (2019)	I4.0, workplace, toxic organisations	Secondary data analysis									√	√
Ancarani et al. (2019)	"Backshoring strategy and the adoption of I4.0"	Secondary data analysis									√	√
Müller et al. (2018)	I4.0, sustainability, SMEs	Survey				√		√		√		√
Kamble et al. (2018)	I4.0, smart manufacturing	LR and Fuzzy approach	√									
Huang et al. (2013)	Additive manufacturing, energy consumption	LR				√						

Source: Author's own work.

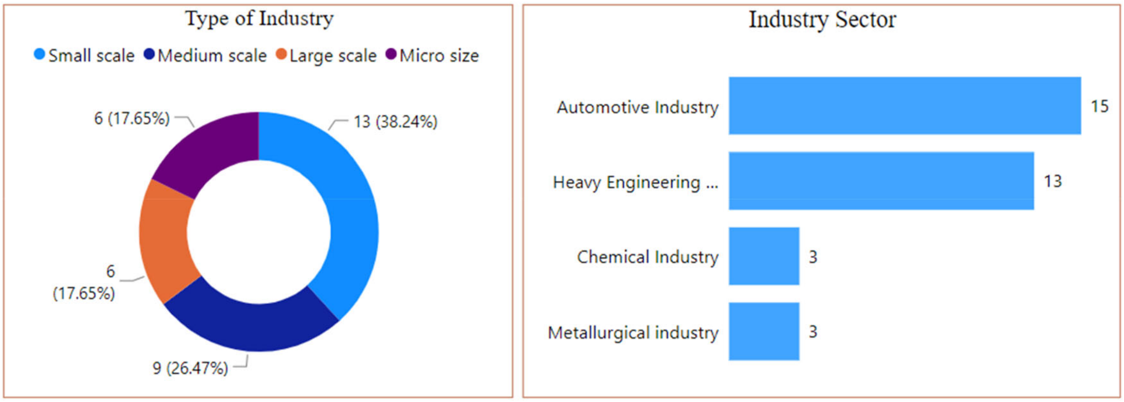

FIGURE 6 Type of industry and their sector. (* Source: Author's own work).

purposefully chosen, ensuring participation from various sectors. The sample includes automotive, heavy engineering, fabrication, chemical, and metallurgical industries. Participants were either key decision-makers or top-level managers from these manufacturing SMEs.

Additionally, we conducted semi-structured interviews with a subset of participants from the questionnaire survey. A semi-structured interview is also a type of qualitative research technique, but it consists of a predetermined set of open-ended questions. Although there is a planned set of questions, the interviewer has the freedom to dig deeper into the particular responses of respondents and ask follow-up questions. Semi-structured interviews balance the rigidity of standard questions and the flexibility of open-ended questions (Kallio et al., 2016), enabling researchers to explore particular topics while allowing respondents to elaborate on their responses.

The integration of these approaches provides a comprehensive perspective on the multifaceted dimensions of I4.0. While the SLR offered a global and theoretical context, the questionnaire survey and semi-structured interviews captured the ground-level realities of manufacturing companies in the manufacturing heartland of India. Together, they contributed to an unbiased examination of the darker side of I4.0, which offered insights, conclusions, and future research recommendations.

5 | RESULTS AND DISCUSSION

The mixed approach that consists of SLR, questionnaire, and semi-structured interviews presented significant insights into the current state of I4.0 implementation and its multifaceted impact on economic, environmental, and social dimensions within the context of sustainability. The findings of this mixed approach are reported in the following sections addressing the RQs listed in the introduction section.

5.1 | RQ 1: What unintended consequences can emerge from the implementation of I4.0 technologies?

The mixed but holistic approach used in this study provided multifaceted insights into the unintended consequences stemming from the technological leap of I4.0.

5.1.1 | High implementation costs

The SLR revealed that integrating I4.0 technologies requires substantial financial investments. The same conclusion resonated in both the questionnaire responses and semi-structured interviews. Organisations, especially SMEs, raised apprehension about the financial burden associated with technological advancements. Figure 7 shows that 79.41% of respondents felt that the initial investment required for implementing I4.0 technologies is an important obstacle for SMEs. Budget constraints often hindered the ability of SMEs to make necessary infrastructure investments and restricted them from participating in the I4.0 revolution. Moreover, in the semi-structured interviews, several respondents emphasised a common sentiment: 'Initial investment to adopt I4.0 is the main concern for small enterprises'.

5.1.2 | Job displacement and workforce transformation

Job displacement emerged as another significant concern as SLR revealed a growing body of evidence on the displacement of traditional jobs by automated systems, and the questionnaire responses further underscored this concern. Around 50% of the respondents acknowledged the potential for job displacement due to automation, especially within the automotive and heavy engineering sectors. On the other hand, participants from the chemical and metallurgical industries expressed a belief that I4.0 might not lead to significant job displacement. While digital technologies and automation promise productivity gains, they also raise concerns about workforce transformation, especially skills gap and training challenges in labour-intensive manufacturing industries. 33 out of 34 respondents (97%) recognised the significance of employee skills and training in the successful implementation of I4.0 practices within their operations. Semi-structured interviews delved deeper, and participants expressed concerns about the social implications of I4.0, emphasising the importance of balancing technological advancements with the preservation of jobs and the well-being of employees. A few important responses from the semi-structured interviews emphasised that: 'The main challenge for SMEs will be cost-benefit balance and in-house technical expertise'.

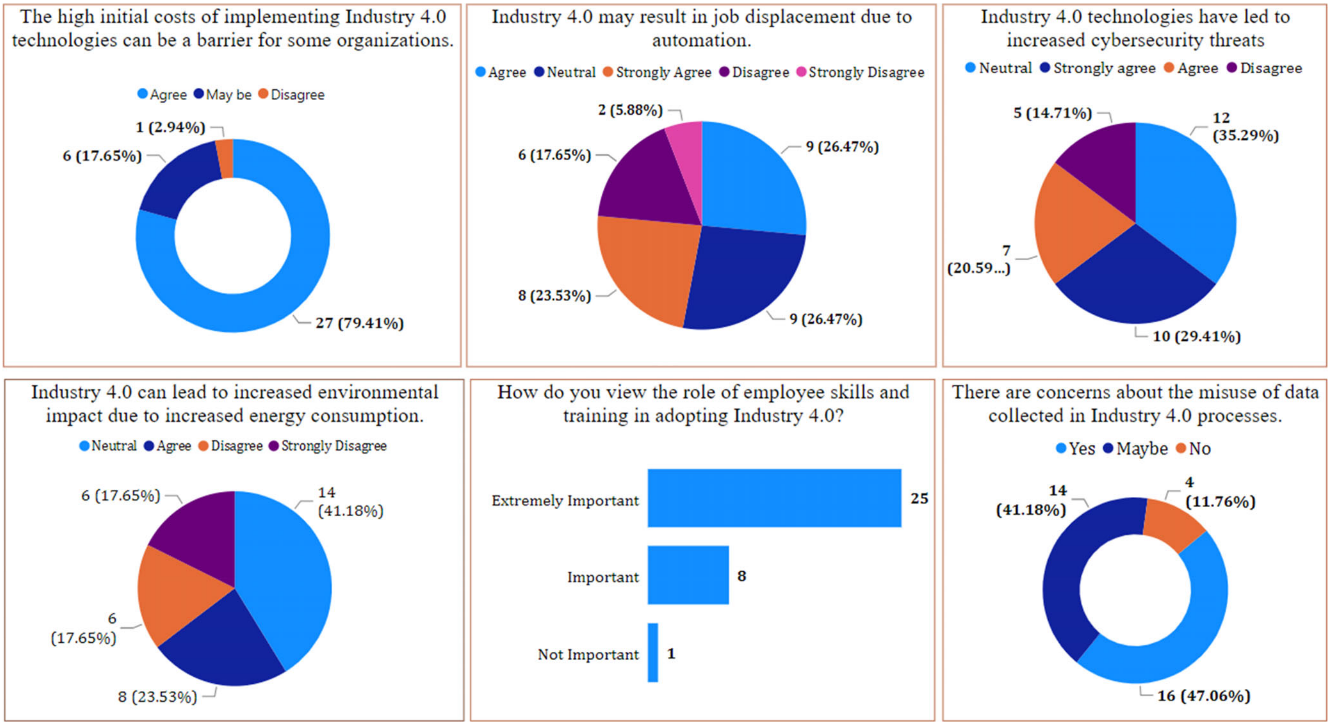

FIGURE 7 Power BI dashboard showing unintended consequences of this I4.0 technological leap. (* Source: Author's own work).

5.1.3 | Cybersecurity issues

Other notable findings of this mixed approach include data security and privacy issues. The SLR revealed that the rapid proliferation of data-driven technologies raised ethical dilemmas related to data ownership and privacy. In order to protect sensitive data, the SLR and questionnaire both underscored the urgent need for strict cybersecurity measures. Again, 50% of the respondents agreed that I4.0 technologies have led to cybersecurity issues, especially within the automotive and heavy engineering sectors. On the other hand, 35.27% remained neutral, and the remaining 14.79% of participants from the chemical and metallurgical industries feel that I4.0 may not cause any significant cyber security concerns. During interviews, a few participants expressed concern about the potential misuse of data acquired from I4.0 technologies, highlighting the pressing need for regulatory frameworks.

5.1.4 | Environmental impact and sustainable practices

The environmental consequences of I4.0 were a focus of SLR and questionnaire responses. The excessive use of energy, natural resources, and electronic waste generation raised concerns about environmental sustainability. Around 41.18% of respondents agreed that I4.0 can lead to environmental impact due to increased energy consumption. Most of them belong to the automotive and heavy engineering industries, but 35.30% of respondents feel that I4.0 may not cause any adverse impact on the environment. The point to be noted here is that most of the 35.30% of respondents belong to either chemical or metallurgical industries. The results of semi-structured interviews show that organisations struggled to strike a balance between technological advancements and environmentally sustainable practices. The challenge lies in designing eco-friendly solutions and minimising the environmental footprint of I4.0 processes.

5.2 | RQ 2: How do the socio-economic and environmental disparities brought by I4.0 contribute to its dark side?

The integration of SLR, a structured questionnaire, and semi-structured interviews has achieved significant insights into the unintended consequences of I4.0. By examining the social, economic, and environmental aspects of TBL sustainability, this study uncovered economic, social, and environmental disparities that underline the darker side of I4.0.

5.2.1 | Economic disparities

The financial burden due to the high initial investment required for the adoption of I4.0 technologies prevented many SMEs from joining the I4.0 revolution, creating an economic disparity where larger enterprises capitalised on the benefits of these technologies while smaller enterprises were left behind. Especially, SMEs face challenges in

TABLE 4 Driving factors and outcomes or severity of various unintended consequences of I4.0.

TBL disparities	Code	Driving factors	Outcomes or severity	Author(s)
Economic disparities	EC1	SMEs struggle with limited financial resources	Restricting SMEs from investments in technology and expansion	Narkhede and Rajhans (2019)
		LEs often dominate markets	Making it difficult for SMEs to compete and gain significant market share.	Chandra et al. (2020)
		LEs can leverage global markets	SMEs are not able to expand internationally	Zahoor et al. (2023)
	EC3	Insufficient evaluation of risks associated with I4.0 technologies and their dependencies	Major supply chain disruptions, SMEs shut their operations	Cragg et al. (2020) and Rajeev (2008)
		Lack of backup systems	Makes operations more susceptible to disruptions, particularly in the case of technical failures or cyberattacks.	Khan et al. (2023)
Social disparities	S1	Industrial robots and automation	Demand for human labour in certain jobs is decreasing	Pasi et al. (2020)
		Skill shift	Those lacking the essential expertise worried about job displacement.	Rajesh (2023)
		Cost efficiency and global competition	Companies are adopting automation to cut costs and stay competitive, potentially leading to downsizing and layoffs.	Acemoglu and Restrepo (2018)
	S2	24/7 connectivity	I4.0 technologies enable constant interaction and remote accessibility, removing boundaries between personal and professional life, No work-life balance	Dalenogare et al. (2018)
		Remote accessibility		Skobelev and Borovik (2017)
	S3	Working across different time zones	Disrupting regular work hours, which affects sleep patterns, further causes health problems.	Aghimien et al. (2020)
Environmental disparities	EN1	Connectivity and data processing (IoT, AI, and BDA)	Consume substantial amounts of energy.	Hariyani and Mishra (2022)
		Cooling systems in data centers		Patyal et al. (2022)
	EN2	Rapid technological advancements	Existing older systems become obsolete, resulting in material waste.	Lu et al. (2022) and Moktadir et al. (2018)
	EN3	Short product lifecycles and incompatibility issues	Technology upgrades might make existing components incompatible, causing premature obsolescence of products, forcing them to be replaced, and resulting in electronic waste.	Moktadir et al. (2018)
		Disposable electronics	Electronic waste in I4.0 applications is on the rise as a result of the disposable electronics trend.	Malik et al. (2023) and Ribeiro et al. (2022)
	EN4	Production of I4.0 technologies	High consumption of rare earth elements	Thapa et al. (2023)
		Resource intensive manufacturing (Additive manufacturing)	Additive manufacturing requires a significant amount of raw materials, which contributes to resource depletion	Ferreira et al. (2023) and Singh et al. (2017)

Source: Author's own work.

balancing the cost–benefit equation and in-house technical expertise, adding an economic dimension to the implementation of I4.0 challenges. Supply chain disruptions driven by technological vulnerabilities further amplify economic disparities, underlining the need for supportive frameworks, policies, and collaborations to bridge the gap between large enterprises and SMEs and ensure equitable access to I4.0 advancements for all.

5.2.2 | Social disparities

The fear of job displacement, particularly in labour-intensive sectors like heavy engineering and the automobile industry, intensifies the social disparity. While the high-skilled workforce can enhance their abilities by reskilling opportunities and adapting to newer technologies, automation poses a significant threat to low-skilled labour jobs, especially in high-population countries. This growing economic disparity not only impacts individuals and their families but also has broader implications for society, potentially leading to social disparity that may result in increased inequality and lack of work-life balance.

5.2.3 | Environmental disparities

Environmental concerns are prevalent, especially in the context of excessive consumption of energy and natural resources, along with electronic waste. While some industries, especially the automotive and heavy engineering industries, have a significant adverse impact on the environment due to their high energy and resource consumption, others, including the chemical and metallurgical sectors, appear comparatively environmentally friendly. However, even these sectors struggle to balance technical developments and environment-friendly alternatives, highlighting disparities in environmental practices. Designing TBL sustainable solutions and reducing the environmental footprint of I4.0 processes pose significant challenges.

The economic, social, and environmental disparities brought by I4.0 technologies create a very complex landscape that demands

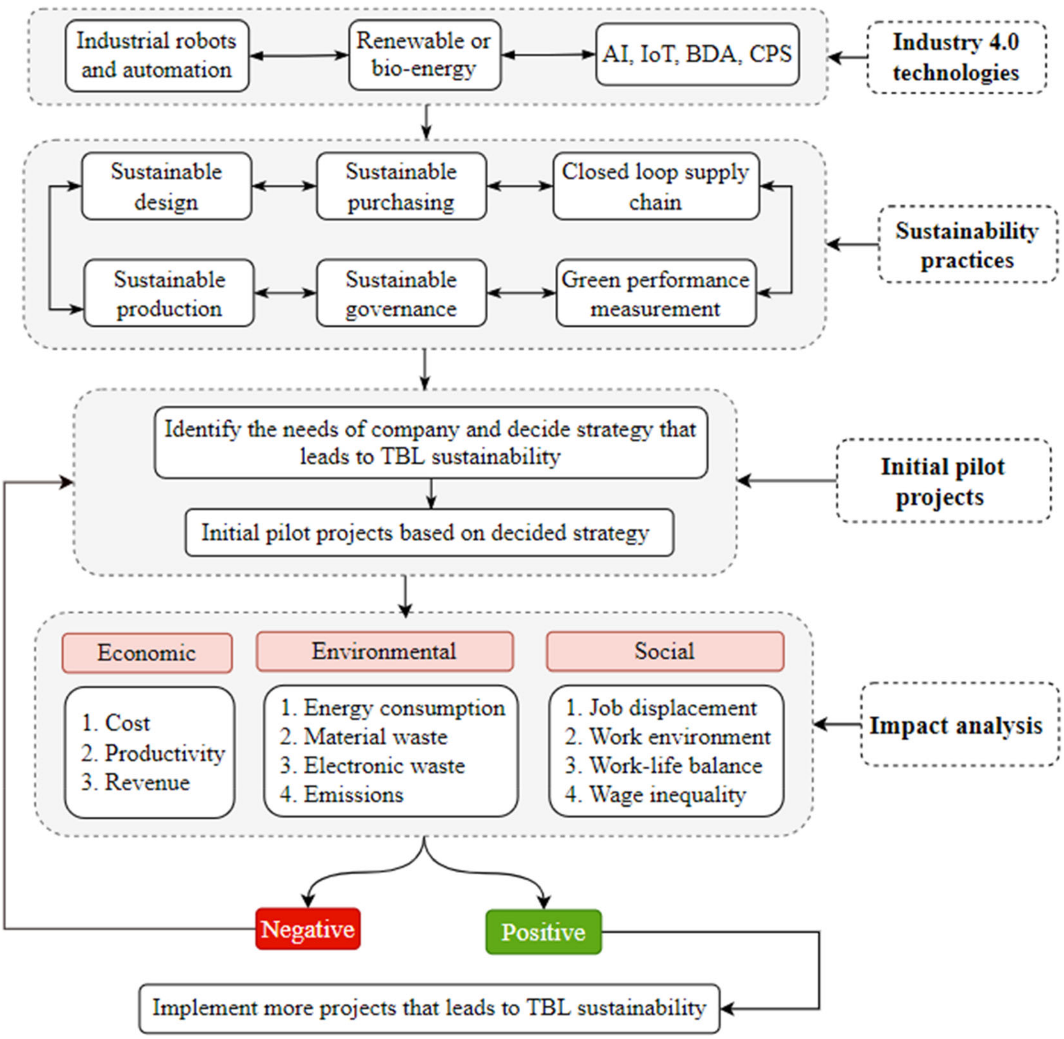

FIGURE 8 Framework for more inclusive and ecologically responsible technological transformation. (* Source: Author's own work).

careful consideration. Bridging these divides is crucial for a seamless transition into the I4.0 era. In this view, policymakers, businessmen, and society need to collaborate to ensure that the benefits of I4.0 are accessible to all, addressing TBL sustainability challenges to create a future where technological advancements will be both inclusive and sustainable. Failing to address these disparities could result in a future where the benefits of I4.0 are overshadowed by its corresponding social and environmental costs, underlining the significance of proactive measures to create a sustainable and balanced technological future. In this view, Table 4 summarises the driving factors and outcomes or severity of TBL disparities.

5.3 | RQ 3: What measures can be implemented to ensure that this current transformation is both inclusive and sustainable?

The research findings present a complex tapestry of TBL discrepancies resulting from the widespread implementation of I4.0. These disparities point out the challenges that various industries face and highlight the need for a framework that will promote a more inclusive and ecologically responsible technological transformation. In this view, a framework is proposed that will guide manufacturing companies to implement I4.0 technologies, emphasising TBL sustainability.

As shown in Figure 8, this framework consists of a structured five-step approach. In the first step, cutting-edge technologies, including AI, IoT, BDA, CPS, 3D printing, robots and automation, and renewable or bio-energy, are used to enhance operational efficiency. The integration of sustainable practices is emphasised in the second step, which ensures that TBL sustainability is woven into the technological framework. This includes developing eco-friendly solutions, reducing energy consumption and waste production, ensuring safe working conditions, and integrating work-life balance. The third step comprises initiating a pilot project based on a thoughtfully developed strategy with an emphasis on sustainability using I4.0 technologies. This pilot project will serve as a testing ground and present insights for further implementing I4.0 practices in manufacturing SMEs. The fourth step includes a thorough impact analysis that assesses the social, environmental, and economic aspects of the pilot project. If the impact analysis exhibits favourable findings, implying positive effects in all dimensions, the fifth step includes the implementation of further projects, scaling up the initiatives to a larger scale. However, if the impact analysis finds negative consequences in any dimension, the framework recommends reconsidering the approach and making the necessary modifications, leading back to step three. This iterative approach ensures a continual cycle of learn-develop-improve that will lead to the I4.0 transformation towards inclusivity and TBL sustainability.

The findings of this study revealed that I4.0 technologies offer significant efficiency gains and other advantages, yet they pose some major hurdles to society and environmental sustainability. Stakeholder engagement can serve a crucial role in mitigating these technological advancement challenges and ensuring the inclusion of social disparities and environmental implications in decision-making processes. However, rapid developments in I4.0 cutting-edge technologies can sometimes overshadow the social and environmental concerns of stakeholders, leading to ethical dilemmas, adverse environmental implications, and social disparities. Therefore, achieving a sustainable equilibrium between stakeholder engagement and technological advancements is imperative to address the darker side of I4.0 and nurture TBL sustainability.

6 | CONCLUSION

This research illuminates the complex landscape of I4.0 penetration in growing economies like India, revealing not only its transformative potential but also the challenges that impede the objective of I4.0. The findings revealed that the technological leap of I4.0 brings unplanned implications that demand careful consideration and holistic solutions. Job displacement and workforce transformation, particularly in labour-intensive sectors, raise significant social implications, demanding a balance between automation and workforce stability. Additionally, the ethical dilemmas about data security and privacy, alongside the environmental impact caused by increased energy consumption, underscore the highly complex structure of I4.0 implementation. Moreover, this paper examines how I4.0 exacerbates economic, social, and environmental inequities. Large enterprises reap the unfair benefits, resulting in economic disparity, while job displacement exacerbates social disparities. Environmental discrepancies further complicate the landscape, underscoring the significance of SD practices in technological developments. A structured five-step approach that emphasises the integration of cutting-edge I4.0 technologies with SD practices has been suggested to address all of these issues. This comprehensive approach incorporates work-life balance, safe working conditions, and environmentally sustainable solutions to pave the way to create a more inclusive and ecologically responsible technological transformation.

This study has significant theoretical and practical implications for integrating I4.0 technologies within the framework of sustainability. The findings of this research contribute theoretically by improving our knowledge of the complex interplay between advances in technology and TBL sustainability. It sheds light on the dark side of I4.0 and encourages further studies on the ethical implications of adopting technological advances and the impact of automation on society. Practically, this research provides valuable insights to industries, policymakers, and educational institutions. Industries can modify their approaches by supporting work-life balance, investing in training for employees and emphasising eco-friendly technologies for SD of enterprises. Policymakers can use these findings to formulate regulations that promote sustainable practices, support SMEs, and deal with social and environmental disparities triggered by the adoption of I4.0. Educational institutions can incorporate the skills required in an evolving job market into their curricula to enhance workforce adaptability. Furthermore, technology experts can innovate in the field of cybersecurity, ensuring the secure application of digital technologies. The significance of cooperation among various stakeholders underscores the need for coordinated efforts to overcome the challenges and direct I4.0 towards inclusive, sustainable, and ethical practices.

Limitations of this study include its limited generalizability and possible participant biases resulting from its exclusive focus on Indian SMEs which might affect result interpretation to other less populated countries. Since this research includes responses from various sectors, the results may lack specificity for particular industries. As a result, sector-specific challenges or nuances pertaining to the darker side of I4.0 and its influence on sustainability may not be adequately documented or thoroughly investigated. In light of these limitations, this research outlines the following future research directions. Future research should delve into examining sector-specific problems and possibilities that could offer valuable insights into long-term impacts on TBL sustainability. Furthermore, it would be imperative to examine how government policies and incentives influence the adoption of I4.0 and its socio-economic consequences in achieving the SD of SMEs. Other promising directions include investigating innovative ways to reduce environmental effects and studying the psychological implications of workforce transformation in the age of digital technology. Additionally, comparative research across nations may shed light on global inequalities and suggest practical and effective solutions according to their challenges.

Based on the insights derived from this study, the authors propose the following punchline that encapsulates the essence of this research study.

> …Harnessing the transformative power of Industry 4.0 requires a careful balance between innovation and sustainability, ensuring a future that is both technologically advanced, socially equitable, economically beneficial, and environmentally conscious…

FUNDING INFORMATION

No external funding is received for this study.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data related to this paper is available with the authors and will be provided upon reasonable request.

ORCID

Ganesh Narkhede https://orcid.org/0000-0002-7190-714X
Vishwas Dohale https://orcid.org/0000-0002-7895-3309

REFERENCES

Acemoglu, D., & Restrepo, P. (2018). The race between man and machine: Implications of technology for growth, factor shares, and employment. *American Economic Review*, *108*(6), 1488–1542. https://doi.org/10.1257/aer.20160696

Aghimien, D. O., Aigbavboa, C. O., Oke, A. E., & Thwala, W. D. (2020). Mapping out research focus for robotics and automation research in construction-related studies: A bibliometric approach. *Journal of Engineering, Design and Technology*, *18*(5), 1063–1079. https://doi.org/10.1108/JEDT-09-2019-0237

Ahmad, S., Wong, K. Y., & Rajoo, S. (2019). Sustainability indicators for manufacturing sectors: A literature survey and maturity analysis from the triple-bottom line perspective. *Journal of Manufacturing Technology Management*, *30*(2), 312–334. https://doi.org/10.1108/JMTM-03-2018-0091

Alhaddi, H. (2015). Triple bottom line and sustainability: A literature review. *Business and Management Studies*, *1*(2), 6. https://doi.org/10.11114/bms.v1i2.752

Alonso-Calero, J. M., Cano, J., & Guerrero-Pérez, M. O. (2021). Is the "green washing" effect stronger than real scientific knowledge? Are we able to transmit formal knowledge in the face of marketing campaigns? *Sustainability*, *14*(1), 285. https://doi.org/10.3390/su14010285

Al-Salman, H. I., & Salih, M. H. (2019). A review cyber of industry 4.0 (cyber-physical systems (CPS), the internet of things (IoT) and the internet of services (IoS)): Components, and security challenges. *Journal of Physics: Conference Series*, *1424*(1), 12029. https://doi.org/10.1088/1742-6596/1424/1/012029

Ancarani, A., Di Mauro, C., & Mascali, F. (2019). Backshoring strategy and the adoption of industry 4.0: Evidence from Europe. *Journal of World Business*, *54*(4), 360–371. https://doi.org/10.1016/j.jwb.2019.04.003

Antony, J., Sony, M., & McDermott, O. (2023). Conceptualizing industry 4.0 readiness model dimensions: An exploratory sequential mixed-method study. *TQM Journal*, *35*(2), 577–596. https://doi.org/10.1108/TQM-06-2021-0180

Atzori, L., Iera, A., & Morabito, G. (2010). The internet of things: A survey. *Computer Networks*, *54*(15), 2787–2805. https://doi.org/10.1016/j.comnet.2010.05.010

Bai, C., Dallasega, P., Orzes, G., & Sarkis, J. (2020). Industry 4.0 technologies assessment: A sustainability perspective. *International Journal of Production Economics*, *229*, 107776. https://doi.org/10.1016/j.ijpe.2020.107776

Bednar, P. M., & Welch, C. (2020). Socio-technical perspectives on smart working: Creating meaningful and sustainable systems. *Information Systems Frontiers*, *22*(2), 281–298. https://doi.org/10.1007/s10796-019-09921-1

Beltrami, M., Orzes, G., Sarkis, J., & Sartor, M. (2021). Industry 4.0 and sustainability: Towards conceptualization and theory. *Journal of Cleaner Production*, *312*, 127733. https://doi.org/10.1016/j.jclepro.2021.127733

Birkel, H. S., Veile, J. W., Müller, J. M., Hartmann, E., & Voigt, K. (2019). Development of a risk framework for industry 4.0 in the context of sustainability for established manufacturers. *Sustainability*, *11*(2), 384. https://doi.org/10.3390/su11020384

Böckin, D., & Tillman, A. M. (2019). Environmental assessment of additive manufacturing in the automotive industry. *Journal of Cleaner Production*, *226*, 977–987. https://doi.org/10.1016/j.jclepro.2019.04.086

Bohnsack, R., Kurtz, H., & Hanelt, A. (2021). Re-examining path dependence in the digital age: The evolution of connected car business models. *Research Policy*, *50*(9), 104328. https://doi.org/10.1016/j.respol.2021.104328

Buhl, H. U., Röglinger, M., Moser, F., & Heidemann, J. (2013). Big data: A fashionable topic with(out) sustainable relevance for research and practice? *Business and Information Systems Engineering*, *5*(2), 65–69. https://doi.org/10.1007/s12599-013-0249-5

Chandra, A., Paul, J., & Chavan, M. (2020). Internationalization barriers of SMEs from developing countries: A review and research agenda. *International Journal of Entrepreneurial Behaviour and Research*, *26*(6), 1281–1310. https://doi.org/10.1108/IJEBR-03-2020-0167

Chiarini, A. (2021). Industry 4.0 technologies in the manufacturing sector: Are we sure they are all relevant for environmental performance? *Business Strategy and the Environment*, *30*(7), 3194–3207. https://doi.org/10.1002/bse.2797

Chichilnisky, G. (1997). What is sustainable development? *Land Economics*, *73*(4), 467–491. https://doi.org/10.2307/3147240

Cirillo, V., Rinaldini, M., Staccioli, J., & Virgillito, M. E. (2021). Technology vs. workers: The case of Italy's industry 4.0 factories. *Structural Change and Economic Dynamics*, *56*, 166–183. https://doi.org/10.1016/j.strueco.2020.09.007

Coldwell, D. A. L. (2019). Negative influences of the 4th industrial revolution on the workplace: Towards a theoretical model of entropic citizen behavior in toxic organizations. *International Journal of Environmental Research and Public Health*, *16*(15), 1–13. https://doi.org/10.3390/ijerph16152670

Cragg, T., McNamara, T., Descubes, I., & Guerin, F. (2020). Manufacturing SMEs, network governance and global supply chains. *Journal of Small Business and Enterprise Development*, *27*(1), 130–147. https://doi.org/10.1108/JSBED-10-2019-0334

Cruz, J. M., & Wakolbinger, T. (2008). Multiperiod effects of corporate social responsibility on supply chain networks, transaction costs, emissions, and risk. *International Journal of Production Economics*, *116*(1), 61–74. https://doi.org/10.1016/j.ijpe.2008.07.011

Culot, G., Orzes, G., Sartor, M., & Nassimbeni, G. (2020). The future of manufacturing: A Delphi-based scenario analysis on industry 4.0. *Technological Forecasting and Social Change*, *157*(December 2019), 120092. https://doi.org/10.1016/j.techfore.2020.120092

Dalenogare, L. S., Benitez, G. B., Ayala, N. F., & Frank, A. G. (2018). The expected contribution of industry 4.0 technologies for industrial performance. *International Journal of Production Economics*, *204*(August), 383–394. https://doi.org/10.1016/j.ijpe.2018.08.019

de Sousa Jabbour, A. B. L., Jabbour, C. J. C., Foropon, C., & Filho, M. G. (2018). When titans meet – Can industry 4.0 revolutionise the environmentally-sustainable manufacturing wave? The role of critical success factors. *Technological Forecasting and Social Change*, *132*(January), 18–25. https://doi.org/10.1016/j.techfore.2018.01.017

Dieste, M., Orzes, G., Culot, G., Sartor, M., & Nassimbeni, G. (2023). The "dark side" of industry 4.0: How can technology be made more sustainable? *International Journal of Operations and Production Management*. https://doi.org/10.1108/IJOPM-11-2022-0754

Dionisio, M., de Souza Junior, S. J., Paula, F., & Pellanda, P. C. (2024). The role of digital social innovations to address SDGs: A systematic review. *Environment, Development and Sustainability*, *26*, 5709–5734. https://doi.org/10.1007/s10668-023-03038-x

Dohale, V., Ambilkar, P., Bilolikar, V., Narkhede, B. E., Kumar, A., & Kumar, A. (2023). Evaluating circular economy and smart technology adoption barriers in the Indian textile and apparel industries using neutrosophic ISM. *Annals of Operations Research*. https://doi.org/10.1007/s10479-023-05651-5

Dohale, V., Gunasekaran, A., Akarte, M. M., & Verma, P. (2022). 52 years of manufacturing strategy: An evolutionary review of literature (1969–2021). *International Journal of Production Research*, *60*(2), 569–594. https://doi.org/10.1080/00207543.2021.1971788

Dohale, V., Kamble, S., Ambilkar, P., Gold, S., & Belhadi, A. (2024). An integrated MCDM-ML approach for predicting the carbon neutrality index in manufacturing supply chains. *Technological Forecasting and Social Change*, *201*, 123243. https://doi.org/10.1016/j.techfore.2024.123243

Durão, L. F. C. S., Christ, A., Zancul, E., Anderl, R., & Schützer, K. (2017). Additive manufacturing scenarios for distributed production of spare parts. *International Journal of Advanced Manufacturing Technology*, *93*(1–4), 869–880. https://doi.org/10.1007/s00170-017-0555-z

Dutta, G., Kumar, R., Sindhwani, R., & Singh, R. K. (2020). Digital transformation priorities of India's discrete manufacturing SMEs: A conceptual study in perspective of Industry 4.0. *Competitiveness Review*, *30*(3), 289–314. https://doi.org/10.1108/CR-03-2019-0031

Ferreira, I. A., Oliveira, J. P., Antonissen, J., & Carvalho, H. (2023). Assessing the impact of fusion-based additive manufacturing technologies on green supply chain management performance. *Journal of Manufacturing Technology Management*, *34*(1), 187–211. https://doi.org/10.1108/JMTM-06-2022-0235

Fosso Wamba, S., Akter, S., Edwards, A., Chopin, G., & Gnanzou, D. (2015). How "big data" can make big impact: Findings from a systematic review and a longitudinal case study. *International Journal of Production Economics*, *165*, 234–246. https://doi.org/10.1016/j.ijpe.2014.12.031

Ghobakhloo, M. (2020). Industry 4.0, digitization, and opportunities for sustainability. *Journal of Cleaner Production*, *252*, 119869. https://doi.org/10.1016/j.jclepro.2019.119869

Ghobakhloo, M., Iranmanesh, M., Grybauskas, A., Vilkas, M., & Petraitė, M. (2021). Industry 4.0, innovation, and sustainable development: A systematic review and a roadmap to sustainable innovation. *Business Strategy and the Environment*, *30*(8), 4237–4257. https://doi.org/10.1002/bse.2867

Gimenez, C., Sierra, V., & Rodon, J. (2012). International Journal of Production Economics Sustainable operations: Their impact on the triple bottom line. *International Journal of Production Economics*, *140*(1), 149–159. https://doi.org/10.1016/j.ijpe.2012.01.035

Goodland, R. (1995). The concept of environmental sustainability. *Annual Review Of Ecology And Systematics*, *26*, 1–24. https://doi.org/10.1146/annurev.es.26.110195.000245

Goswami, M., & Daultani, Y. (2022). Make-in-India and industry 4.0: Technology readiness of select firms, barriers and socio-technical implications. *TQM Journal*, *34*(6), 1485–1505. https://doi.org/10.1108/TQM-06-2021-0179

Grigore, G., Molesworth, M., Miles, C., & Glozer, S. (2021). (un)resolving digital technology paradoxes through the rhetoric of balance. *Organization*, *28*(1), 186–207. https://doi.org/10.1177/1350508420968196

Grybauskas, A., Stefanini, A., & Ghobakhloo, M. (2022). Social sustainability in the age of digitalization: A systematic literature review on the social implications of industry 4.0. *Technology in Society*, *70*(May), 101997. https://doi.org/10.1016/j.techsoc.2022.101997

Hami, N., Muhamad, M. R., & Ebrahim, Z. (2015). The impact of sustainable manufacturing practices and innovation performance on economic sustainability. *Procedia CIRP*, *26*, 190–195. https://doi.org/10.1016/j.procir.2014.07.167

Hariyani, D., & Mishra, S. (2022). Barriers to the adoption of integrated sustainable-green-lean-six sigma-agile manufacturing system (ISGLSAMS): A literature review. *Benchmarking*, *30*, 3590–3636. https://doi.org/10.1108/BIJ-10-2021-0585

Heidrich, O., & Tiwary, A. (2013). Environmental appraisal of green production systems: Challenges faced by small companies using life cycle assessment. *International Journal of Production Research*, *51*(19), 5884–5896. https://doi.org/10.1080/00207543.2013.807372

Hopkins, N., Jiang, L., & Brooks, H. (2021). Energy consumption of common desktop additive manufacturing technologies. *Cleaner Engineering and Technology*, *2*(February), 100068. https://doi.org/10.1016/j.clet.2021.100068

Horváth, D., & Szabó, R. Z. (2019). Driving forces and barriers of industry 4.0: Do multinational and small and medium-sized companies have equal opportunities? *Technological Forecasting and Social Change*, *146*(March), 119–132. https://doi.org/10.1016/j.techfore.2019.05.021

Hozdić, E. (2015). Smart factory for industry 4.0: A review. *International Journal of Modern Manufacturing Technologies*, *VII*(1), 28–35.

Huang, S. H., Liu, P., Mokasdar, A., & Hou, L. (2013). Additive manufacturing and its societal impact: A literature review. *International Journal of Advanced Manufacturing Technology*, *67*(5–8), 1191–1203. https://doi.org/10.1007/s00170-012-4558-5

Kallio, H., Pietilä, M., Johnson, M., & Kangasniemi, M. (2016). Systematic methodological review: Developing a framework for a qualitative semi-structured interview guide. *Journal of Advanced Nursing*, *72*(12), 2954–2965. https://doi.org/10.1111/jan.13031

Kamble, S. S., Gunasekaran, A., & Gawankar, S. A. (2018). Sustainable industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives. *Process Safety and Environmental Protection*, *117*, 408–425. https://doi.org/10.1016/j.psep.2018.05.009

Khan, H. Z., Bose, S., Mollik, A. T., & Harun, H. (2021). "Green washing" or "authentic effort"? An empirical investigation of the quality of sustainability reporting by banks. *Accounting, Auditing and Accountability Journal*, *34*(2), 338–369. https://doi.org/10.1108/AAAJ-01-2018-3330

Khan, M., Haleem, A., & Javaid, M. (2023). Changes and improvements in industry 5.0: A strategic approach to overcome the challenges of industry 4.0. *Green Technologies and Sustainability*, *1*(2), 100020. https://doi.org/10.1016/j.grets.2023.100020

Khanfar, A. A., Iranmanesh, M., Ghobakhloo, M., Senali, M. G., & Fathi, M. (2020). Applications of blockchain technology in sustainable manufacturing and supply chain management: A systematic review. *Sustainability*, *13*(14), 7870. https://doi.org/10.3390/su13147870

Kok, J. N., Boers, E. J. W., Kosters, W. A., van Der Putten, P., & Poel, M. (2009). Artificial intelligence: Definition, trends, techniques and cases. *Encyclopedia of Life Support Systems (EOLSS)*, *1*, 1096–1097. https://www.eolss.net/Sample-Chapters/C15/E6-44.pdf

Kumar, T. (2017). Achieving sustainable development through environment accounting from the global perspective: Evidence from Bangladesh. *Asian Journal of Accounting Research*, *2*(1), 45–61. https://doi.org/10.1108/AJAR-2017-02-01-B005

Lee, J., Bagheri, B., & Kao, H. A. (2015). A cyber-physical systems architecture for industry 4.0-based manufacturing systems. *Manufacturing Letters*, *3*, 18–23. https://doi.org/10.1016/j.mfglet.2014.12.001

Li, B. H., Hou, B. C., Yu, W. T., Lu, X. B., & Yang, C. W. (2017). Applications of artificial intelligence in intelligent manufacturing: A review. *Frontiers of Information Technology and Electronic Engineering*, *18*(1), 86–96. https://doi.org/10.1631/FITEE.1601885

Lu, H., Zhao, G., & Liu, S. (2022). Integrating circular economy and industry 4.0 for sustainable supply chain management: A dynamic capability view. *Production Planning and Control*, *35*(2), 170–186. https://doi.org/10.1080/09537287.2022.2063198

Maddikunta, P. K. R., Pham, Q. V., Deepa, N., Dev, K., Gadekallu, T. R., Ruby, R., & Liyanage, M. (2022). Industry 5.0: A survey on enabling technologies and potential applications. *Journal of Industrial Information Integration*, *26*(February), 100257. https://doi.org/10.1016/j.jii.2021.100257

Malik, A., Sharma, S., Batra, I., Sharma, C., Kaswan, M. S., & Garza-Reyes, J. A. (2023). Industrial revolution and environmental sustainability: An analytical interpretation of research constituents in industry 4.0. *International Journal of Lean Six Sigma.*, *15*, 22–49. https://doi.org/10.1108/IJLSS-02-2023-0030

Margherita, E. G., & Braccini, A. M. (2020). Industry 4.0 technologies in flexible manufacturing for sustainable organizational value: Reflections from a multiple case study of Italian manufacturers. *Information Systems Frontiers*, *25*, 995–1016. https://doi.org/10.1007/s10796-020-10047-y

Moktadir, M. A., Rahman, T., Rahman, M. H., Ali, S. M., & Paul, S. K. (2018). Drivers to sustainable manufacturing practices and circular economy: A perspective of leather industries in Bangladesh. *Journal of Cleaner Production*, *174*, 1366–1380. https://doi.org/10.1016/j.jclepro.2017.11.063

Monostori, L. (2003). AI and machine learning techniques for managing complexity, changes and uncertainties in manufacturing. *Engineering Applications of Artificial Intelligence*, *16*(4), 277–291. https://doi.org/10.1016/S0952-1976(03)00078-2

Müller, J. M., Buliga, O., & Voigt, K. I. (2018). Fortune favors the prepared: How SMEs approach business model innovations in industry 4.0. *Technological Forecasting and Social Change*, *132*, 2–17. https://doi.org/10.1016/j.techfore.2017.12.019

Müller, J. M., & Voigt, K. I. (2018). Sustainable industrial value creation in SMEs: A comparison between industry 4.0 and made in China 2025. *International Journal of Precision Engineering and Manufacturing—Green Technology*, *5*(5), 659–670. https://doi.org/10.1007/s40684-018-0056-z

Narkhede, G., & Chinchanikar, S. (2024). *Role of Industry 5.0 for driving sustainability in the manufacturing sector: An emerging research agenda*. https://doi.org/10.1108/JSMA-06-2023-0144

Narkhede, G., Pasi, B., Rajhans, N., & Kulkarni, A. (2023). Industry 5.0 and the future of sustainable manufacturing: A systematic literature review. *Business Strategy and Development*, *6*(4), 704–723. https://doi.org/10.1002/bsd2.272

Narkhede, G., & Rajhans, N. (2019). Insights on supply chain needs and issues in Indian SMEs. *Industrial Engineering Journal*, *12*(2), 1–9. https://doi.org/10.26488/iej.12.2.1174

Nascimento, D. L. M., Alencastro, V., Quelhas, O. L. G., Caiado, R. G. G., Garza-Reyes, J. A., Lona, L. R., & Tortorella, G. (2019). Exploring industry 4.0 technologies to enable circular economy practices in a manufacturing context: A business model proposal. *Journal of Manufacturing Technology Management*, *30*(3), 607–627. https://doi.org/10.1108/JMTM-03-2018-0071

Nunes, M. L., Pereira, A. C., & Alves, A. C. (2017). Smart products development approaches for industry 4.0. *Procedia Manufacturing*, *13*, 1215–1222. https://doi.org/10.1016/j.promfg.2017.09.035

Oláh, J., Aburumman, N., Popp, J., Khan, M. A., Haddad, H., & Kitukutha, N. (2020). Impact of industry 4.0 on environmental sustainability. *Sustainability (Switzerland)*, *12*(11), 1–21. https://doi.org/10.3390/su12114674

Oztemel, E., & Gursev, S. (2020). Literature review of industry 4.0 and related technologies. *Journal of Intelligent Manufacturing*, *31*(1), 127–182. https://doi.org/10.1007/s10845-018-1433-8

Pasi, B. N., Mahajan, S. K., & Rane, S. B. (2020). The current sustainability scenario of industry 4.0 enabling technologies in Indian manufacturing industries. *International Journal of Productivity and Performance Management*, *70*(5), 1017–1048. https://doi.org/10.1108/IJPPM-04-2020-0196

Patyal, V. S., Sarma, P. R. S., Modgil, S., Nag, T., & Dennehy, D. (2022). Mapping the links between industry 4.0, circular economy and sustainability: A systematic literature review. *Journal of Enterprise Information Management*, *35*(1), 1–35. https://doi.org/10.1108/JEIM-05-2021-0197

Pegoraro, D., De Propris, L., & Chidlow, A. (2022). Regional factors enabling manufacturing reshoring strategies: A case study perspective. *Journal of International Business Policy*, *5*(1), 112–133. https://doi.org/10.1057/s42214-021-00112-x

Queiroz, M. M., Telles, R., & Bonilla, S. H. (2020). Blockchain and supply chain management integration: A systematic review of the literature. *Supply Chain Management*, *25*(2), 241–254. https://doi.org/10.1108/SCM-03-2018-0143

Rajeev, N. (2008). Do inventory management practices affect economic performance? An empirical evaluation of the machine tool smes in bangalore. *International Journal of Management Science and Engineering Management*, *3*(4), 312–320. https://doi.org/10.1080/17509653.2008.10671058

Rajesh, R. (2023). Industry 5.0: Analyzing the challenges in implementation using grey influence analysis. *Journal of Enterprise Information Management*, *36*(5), 1349–1371. https://doi.org/10.1108/JEIM-03-2023-0121

Ramya, A., & Vanapalli, S. L. (2016). 3D printing technologies in various applications. *International Journal of Mechanical Engineering and Technology*, *7*(3), 396–409.

Ribeiro, J., Lima, R., Eckhardt, T., & Paiva, S. (2021). Robotic process automation and artificial intelligence in industry 4.0—A literature review. *Procedia Computer Science*, *181*(2019), 51–58. https://doi.org/10.1016/j.procs.2021.01.104

Ribeiro, J. N., Melo Barbosa, A. F., Nardy Ribeiro, A. V. F., Godoi Pereira, M., de Oliveira, J. P., Zordan, A. B., & da Silva, A. R. (2022). E-waste and its consequence for environment and public health: Perspectives in COVID-19 pandemic times. *Global Journal of Health Science*, *14*(3), 54. https://doi.org/10.5539/gjhs.v14n3p54

Rodriguez, I., Mogensen, R. S., Fink, A., Raunholt, T., Markussen, S., Christensen, P. H., Berardinelli, G., Mogensen, P., Schou, C., & Madsen, O. (2021). An experimental framework for 5G wireless system integration into industry 4.0 applications. *Energies*, *14*(15), 1–23. https://doi.org/10.3390/en14154444

Rožanec, J. M., Novalija, I., Zajec, P., Kenda, K., Tavakoli Ghinani, H., Suh, S., Veliou, E., Papamartzivanos, D., Giannetsos, T., Menesidou, S. A., Alonso, R., Cauli, N., Meloni, A., Recupero, D. R., Kyriazis, D., Sofianidis, G., Theodoropoulos, S., Fortuna, B., Mladenić, D., & Soldatos, J. (2022). Human-centric artificial intelligence architecture for industry 5.0 applications. *International Journal of Production Research*, *1–26*, 6847–6872. https://doi.org/10.1080/00207543.2022.2138611

Ruiz-Blanco, S., Romero, S., & Fernandez-Feijoo, B. (2022). Green, blue or black, but washing–what company characteristics determine greenwashing? *Environment, Development and Sustainability*, *24*(3), 4024–4045. https://doi.org/10.1007/s10668-021-01602-x

Sartal, A., Bellas, R., Mejías, A. M., & García-Collado, A. (2020). The sustainable manufacturing concept, evolution and opportunities within industry 4.0: A literature review. *Advances in Mechanical Engineering*, *12*(5), 168781402092523. https://doi.org/10.1177/1687814020925232

Schneider, S., & Kokshagina, O. (2021). Digital transformation: What we have learned (thus far) and what is next. *Creativity and Innovation Management*, *30*(2), 384–411. https://doi.org/10.1111/caim.12414

Sharma, R., Jabbour, C. J. C., de Sousa, L., & Jabbour, A. B. (2020). Sustainable manufacturing and industry 4.0: What we know and what we don't. *Journal of Enterprise Information Management*, *34*(1), 230–266. https://doi.org/10.1108/JEIM-01-2020-0024

Sidhu, S. S., Singh, K., & Ahuja, I. S. (2022). Ranking of implementation dimensions for maintenance practices in Northern Indian SMEs using integrated AHP-TOPSIS approach. *Journal of Small Business and Entrepreneurship*, *34*(2), 175–194. https://doi.org/10.1080/08276331.2020.1809220

Singh, S., Ramakrishna, S., & Singh, R. (2017). Material issues in additive manufacturing: A review. *Journal of Manufacturing Processes*, *25*, 185–200. https://doi.org/10.1016/j.jmapro.2016.11.006

Skobelev, P., & Borovik, Y. (2017). On the way from industry 4 .0 to industry 5.0. *International Scientific Journal "Industry 4.0,"*, *2*(6), 307–311. https://stumejournals.com/journals/i4/2017/6/307/pdf

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, *104*(July), 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039

Souza, R., Ferenhof, H., & Forcellini, F. (2022). Industry 4.0 and industry 5.0 from the lean perspective. *International Journal of Management, Knowledge and Learning*, *11*(June), 145–155. https://doi.org/10.53615/2232-5697.11.145-155

Stentoft, J., Wickstrøm, K. A., Philipsen, K., & Haug, A. (2021). Drivers and barriers for Industry 4.0 readiness and practice: empirical evidence from small and medium-sized manufacturers. *Production Planning & Control*, *32*(10), 811–828. https://doi.org/10.1080/09537287.2020.1768318

Susitha, E., & Nanayakkara, M. (2023). Impact of green supply chain management practices on the triple bottom line: A study on apparel manufacturers of Sri Lanka. *Journal of Asia Business Studies*, *17*(6), 1228–1249. https://doi.org/10.1108/JABS-05-2022-0180

Thapa, K., Vermeulen, W. J. V., Deutz, P., & Olayide, O. (2023). Ultimate producer responsibility for e-waste management–A proposal for just transition in the circular economy based on the case of used European electronic equipment exported to Nigeria. *Business Strategy and Development*, *6*(1), 33–52. https://doi.org/10.1002/bsd2.222

Thoben, K. D., Wiesner, S. A., & Wuest, T. (2017). "Industrie 4.0" and smart manufacturing-a review of research issues and application examples. *International Journal of Automation Technology*, *11*(1), 4–16. https://doi.org/10.20965/ijat.2017.p0004

Trappey, A. J. C., Trappey, C. V., Govindarajan, U. H., Sun, J. J., & Chuang, A. C. (2016). A review of technology standards and patent portfolios for enabling cyber-physical systems in advanced manufacturing. *IEEE Access*, *4*, 7356–7382. https://doi.org/10.1109/ACCESS.2016.2619360

UN. (2015). *THE 17 GOALS—Sustainable Development Goals*.

Veleva, V., & Ellenbecker, M. (2001). Indicators of sustainable production: Framework and methodology. *Journal of Cleaner Production*, *9*(6), 519–549. https://doi.org/10.1016/S0959-6526(01)00010-5

Vera-Baquero, A., Colomo-Palacios, R., & Molloy, O. (2014). Towards a process to guide big data based decision support systems for business processes. *Procedia Technology*, *16*(2212), 11–21. https://doi.org/10.1016/j.protcy.2014.10.063

Wang, J., Xu, C., Zhang, J., & Zhong, R. (2022). Big data analytics for intelligent manufacturing systems: A review. *Journal of Manufacturing Systems*, *62*(March), 738–752. https://doi.org/10.1016/j.jmsy.2021.03.005

Xiao, Y., & Watson, M. (2019). Guidance on conducting a systematic literature review. *Journal of Planning Education and Research*, *39*(1), 93–112. https://doi.org/10.1177/0739456X17723971

Zahoor, N., Khan, H., Donbesuur, F., Khan, Z., & Rajwani, T. (2023). Grand challenges and emerging market small and medium enterprises: The role of strategic agility and gender diversity. *Journal of Product Innovation Management*, *41*, 473–500. https://doi.org/10.1111/jpim.12661

Zhang, L., Jeong, D., & Lee, S. (2021). Data quality management in the internet of things. *Sensors*, *21*(17), 1–21. https://doi.org/10.3390/s21175834

Zheng, T., Ardolino, M., Bacchetti, A., & Perona, M. (2021). The applications of industry 4.0 technologies in manufacturing context: A systematic literature review. *International Journal of Production Research*, *59*(6), 1922–1954. https://doi.org/10.1080/00207543.2020.1824085

How to cite this article: Narkhede, G., Dohale, V., & Mahajan, Y. (2024). Darker side of industry 4.0 and its impact on triple-bottom-line sustainability. *Sustainable Development*, 1–18. https://doi.org/10.1002/sd.3009