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Industry 4.0 innovations and their implications: An evaluation from sustainable development perspective

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A R T I C L E I N F O

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A B S T R A C T

As the dyad of Industry 4.0 (I4.0) and innovation have gained greater attention from researchers, practitioners and policy makers, integration of sustainability and sustainable development paradigms to this dyad have become fundamental to sustain businesses' competitive advantage. A variety of I4.0 based innovations with several sustainability implications exists in the literature, but they largely address independent and distinct knowledge areas, which yields an opportunity to explore the interconnections of I4.0-innovation-sustainability nexus. Therefore, this research performs a systematic literature review to synthesize the nexus by investigating how a combination of I4.0 technologies and different types of innovations, could contribute to sustainable development thereby providing sustainability implications. Our review portfolio derived from three databases analyzed 58 journal articles that addressed the simultaneous links of I4.0-innovation-sustainability. The primary findings show that I4.0 results in various innovation types including process, product, business model, supply chain, organizational, open, and marketing innovations that advance triple bottom line (TBL) sustainability, circular economy (CE), sustainable business models (SBMs) and achievement of sustainable development goals (SDGs). While most studies focus on process, product, and business model innovations with TBL and CE implications, more research is required to address the significant but overlooked areas such as open, organizational, and marketing innovations to advance business model sustainability and SDGs.

1. Introduction

The fourth industrial revolution, also known as industry 4.0 (I4.0) (Kagermann et al., 2013; Hermann et al., 2016) is recognized for its disruptive technologies and growing intelligence. The most predominant I4.0 technologies include internet of things (IoT), cyber-physical systems (CPS), big data (BD), cloud computing (CC) additive manufacturing also known as 3D printing, robotics, and artificial intelligence (AI) (Dalenogare et al., 2018; Frank et al., 2019). These technologies are known for their potential to enhance flexibility (Dalenogare et al., 2018), augment efficiency (de Sousa Jabbour et al., 2018), improve resource sharing (Liu and Xu, 2017) and boost competitiveness and overall growth of the organizations (Stock and Seliger, 2016) through their real-time data interchange architecture (Li et al., 2017; Thoben et al., 2017; Yu et al., 2015).

The concept of I4.0 is quite interchangeably used for advanced or smart manufacturing, and it has proven to be a powerful driver of innovation for products and services due to its fast-paced technological advancements and implementation (Frank et al., 2019) in processes (De Giovanni and Cariola, 2021), organizations (Dalenogare et al., 2018), their supply chains (Hahn, 2020) and overall business models (Ibarra et al., 2018) across various sectors. Together, the contemporary digital technologies used in I4.0 and resulting innovations have further shown remarkable potential towards sustainable industrial value creation by improving economic components such as resource efficiency as well as overcoming environmental and social constraints necessary for sustainable development (SD) (Bonilla et al., 2018).

While innovations and I4.0 are intertwined concepts, I4.0 and sustainability are relatively recent emerging but major trends in sustainable production literature (Luthra and Mangla, 2018; Bai et al., 2020; Dubey et al., 2019). The intersection of I4.0, resulting innovations and their sustainability implications are acknowledged both in synergy and as overlapping concepts that highlight several micro and macro innovative and sustainable manufacturing opportunities (Stock and Seliger, 2016).

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The micro-opportunities are known as innovating the product design and processes through CPS and efficient identification systems enabling the resource efficiency of the process chains and the use of circular economy (CE) principles of closed loop supply chains (Swat et al., 2014; Rajput and Singh, 2019). The macro-opportunities, in turn, comprise blockchain for multinational enterprises and developing economies (Ajwani-Ramchandani et al., 2021; Torres de Oliveira et al., 2020) and smart data based new sustainable business models characterizing innovation and competitiveness in long-run, at the same time reducing the negative impacts for society and environment (Bocken et al., 2014; Schaltegger and Wagner, 2011; Stock and Seliger, 2016).

There are a few recent review studies in the same research stream (Ching et al., 2022; Ghobakhloo et al., 2021; Dantas et al., 2021; Silvestri et al., 2020; Rosa et al., 2020) that investigate the impact of I4.0 technologies and innovations on various sustainability aspects, such as I4.0 for CE (Rosa et al., 2020) and SDGs (Dantas et al., 2021), sustainable manufacturing functions (Ching et al., 2022), maintenance management (Silvestri et al., 2020) and organizational and social sustainability aspects (Ghobakhloo et al. (2021). However, accepting the significance, relevance, and timeliness of these topics, recent studies suggest a careful evaluation of each I4.0 technology for innovation and its variable influence on sustainability impact (Bai et al., 2020; Mubarak et al., 2021) as the strength of the relationship between I4.0, innovations and SD is still unknown (Piccarozzi et al., 2022). To address this research gap, we opt for a combined and systematic review approach to analyze these mega trends in this study. First, an overview of the relationship between I4.0 technologies and various forms of innovation for sustainable development is presented. Second, seven different types of innovation outcomes of I4.0 are identified. Third, a summary of the various forms of innovation in relation to key I4.0 technologies and their distinct sustainability implications is provided. Fourth, valuable insights into how future research can be focused to better understand the connection between Industry 4.0 technologies and different types of innovations for sustainable development are identified.

The aim of exploring this emerging trio of I4.0, innovations and SD is to understand how I4.0 leads to a variety of innovation types including new products and processes and advanced business models which further provide implications for TBL sustainability, CE, SBMs, corporate social responsibility, and support the achievement of the SDGs. Furthermore, besides the economic viewpoint, we are interested in how I4.0 based innovations in organizations and value networks can contribute to social and environmental sustainability, because of growing inequality in societies, climate crisis and environmental problems around the world (United Nations, 2020 & 2021). In summary, the core objective is to address the nexus of I4.0 and different forms of innovations and their combined impact on subsequent sustainable development trends. This synergetic analysis of I4.0 technologies, design postulations for innovations and the underlying sustainability inferences will result in determining the impact of I4.0 at the firm and value chain levels contributing to sustainable development (Ching et al., 2022).

In this research, we define I4.0 as an information technology-based innovative manufacturing system designed and implemented to advance productivity and sustainable development (Khan et al., 2021a, b). Therein, innovation is defined as an outcome which may consist of a product, process, idea, and a concept introduced in the new environment (Marcus, 1988; Howell and Higgins, 1990) predominantly emphasizing on what output is sought (Kahn, 2018) in terms of being novel and useful. Sustainable development is elaborated as an umbrella term reflecting on multidimensional and collective steering processes for several interested parties (Khan et al., 2021a,b) where sustainability is used as a discourse to achieve the goals defined for SD (Sartori et al., 2014). We strategically chose these broad research terms for analysis to grasp a holistic and comprehensive understanding of different viewpoints on I4.0 based innovations for sustainability in the current literature. Acknowledging the contributions of prior research and the need for combined view on I4.0, innovations and their sustainability implications, the primary research question of this study is:

What are the diverse types of I4.0-enabled innovations and how do they impact different aspects of sustainability and sustainable development?

This paper is organized as follows: The introduction (section 1) is followed by a brief literature background (section 2) explaining how I4.0, innovations and SD are defined and framed within the scope of current research. Thereafter, section 3 presents the systematic literature review method employed in this study. The review results are presented in section 4 where key I4.0 innovations are identified, each with their contribution to distinct sustainability implications. Section 5 presents and discusses content and thematic analysis of the I4.0-innovations-sustainability nexus. Future research directions are presented in section 6, followed by conclusion including implications and limitations in section 7.

2. Background

The manufacturing realm has continuously been advanced with the developments of science and technology resulting into increased industrialization around the globe (Belvedere et al., 2013). While there is no universal agreement on what are those advances which institute an industrial revolution (Kagermann et al., 2013), there are four common industrial revolutions evaluated based on technological evolutions in the past centuries. The first industrial revolution introduces water and steam-power technologies, while the second and third revolutions developed electric mass production technologies and the application of information technology (IT) and electronics for automation (Drath and Horch, 2014), respectively.

The fourth industrial revolution, I4.0, introduced by the German government in 2011 is associated with improving the efficiency of production and management processes in order to raise profitability (Lichtblau et al., 2015). It is based on developing a cyber-physical system (CPS) to create a digital and smart factory, resulting in a highly flexible production model of customized and digitized products and services, with continuous interactions between people, products, and devices throughout the manufacturing process (Kagermann et al., 2013). Smart factories make work (with increasingly complicated processes) simpler for the people who work in them, while also guaranteeing that manufacturing may be attractive, sustainable in an urban context, and lucrative (Kagermann et al., 2013). The wide-spread I4.0 technologies such as Additive Manufacturing (AM), Artificial Intelligence (AI), Artificial Vision (AV), Big Data (BD) and Advance Analysis (AA), Cybersecurity, Internet of Things (IoT), Robotics, Virtual and Augmented Reality (VAR) (De Sousa Jabbour et al., 2018; Laskurain-Iturbe et al., 2021; Zhang and Chen, 2020) have gained increased research interest and provided numerous benefits for a large number of organizations (Oztemel and Gursev., 2020).

The advent of I4.0 is characterized by intelligent industrialization and high-end digitalization through the integration of devices, data, and processes to increase connectivity and communication between humans, machines, and production facilities (Sanchez et al., 2020; Fakhri et al., 2020; Harrison et al., 2016). These technological advancements have aided in the transition to more open, collaborative, and network-centric innovation approaches (Christensen and Maskell, 2003). The extant literature suggests that the I4.0 characterization, based on the integration principles promotes innovation for the industries (Kagermann et al., 2013) regarding products, processes, supply chains, business models and overall organizations. For instance, CPS is entitled to enhance the productivity and decision-making processes of the companies through faster adaptations to production-line breakages and efficient resource utilization (Schuh et al., 2017; Jeschke et al., 2017) and AM is applied to co-design of products thus contributing to customization and innovation (Weller et al., 2015). Other technologies such as simulations are used for commissioning the properties of an implemented model (Saldivar et al., 2015), BD for predictive analysis (Javaid et al., 2021) and cloud computing (CC) to transform 3D models into physical products which facilitate the on-demand processes of the manufacturing systems (Weller et al., 2015; Wang et al., 2016). The adoption and implementation of these technological innovations have shown results throughout the value chain starting from the robustness of the factory-floor (Sanchez et al., 2020; Tripathi et al., 2022) to the transformation of more scalable and flexible supply-base (Hahn, 2020) and delivering value to the customers through mass customization (Ibarra et al., 2018). These transformation for the value-creation involve extensive changes in the technical and production systems emerging through the integration of technological innovations and new business models comprising collaborative environments, enhanced customer relationships and new product-service offerings.

In recent years, the I4.0 paradigm is not only limited to its innovation advancements but has taken a step forward to more sustainable industrial value-creation. For example, Dev et al. (2020) created a classic model of innovation diffusion to describe how I4.0 may simplify the reverse supply chain in a product diffusion environment that is sustainable. Liu and De Giovanni (2019) proved with mathematical modelling the importance of I4.0 technologies to sustainability performance by incorporating green process innovation. Chen et al. (2021) discovered that technology improvements within the I4.0 paradigm increase energy efficiency. Ghobakhloo and Fathi (2021), for example, provided comparable insights into the contributions of Industry 4.0 technical breakthroughs to energy sustainability. Mubarak et al. (2021) reported I4.0 based sustainable innovation specifically from an open innovation perspective, some of which are green process innovation capacity, green product innovation capacity, product life-cycle management capability, sustainable innovation orientation development, sustainable partnership and collaboration, and value chain integration (Ghobakhloo et al., 2021). Some researchers have sought to identify a variety of digital technologies that can be used to assist open innovation (Adamides, and Karacapilidis, 2020) such as data mining, simulation, mock - ups, and visual analytics technologies that assist open innovation in new product development (Dodgson et al., 2006), and innovation platforms to reach dispersed "crowd" gather ideas for new products and services (Di Gangi, and Wasko, 2009).

The current research trends show a significant cross-over and linkage of I4.0, various product, process and organizational innovations for sustainable development comprising different perspectives on sustainability implications for economy, environment and society (Müller, 2021), sustainable supply chains (Luthra and Mangla, 2018), circular economy (Yu et al., 2022; Rajput and Singh, 2019) and sustainable business models (Khan et al., 2021a,b; Shakeel et al., 2020; De Man and Strandhagen, 2017). However, there is a limited insight available on the synthesized interplay of I4.0-innovation-sustainability and a lack of systematic analysis of I4.0 innovation outcomes with respect to sustainability implications. This paper thus analyses a wide set of academic literature to extract the current state of I4.0-enabled innovations that contribute to sustainable development to address the aforementioned gaps and to provide future research directions.

3. Method

In order to produce an unbiased study, this research employs a systematic literature review (SLR) technique to gather data using a scientific process. The SLR denotes a replicable but scientific and transparent method, based on comprehensive literature searches which increases the methodological rigour and reliability through the review process (Mulrow, 1994; Cook et al., 1997; Hart, 1998; Tranfield et al., 2003). The chosen methodology (SLR) is aligned with the goal of this research, which is the knowledge development process through summarizing previous research, finding knowledge gaps, and establishing the context for a new research undertaking (Kitchenham et al., 2009). The research procedure started with planning the research protocol, followed by conducting and analysing the search query with certain inclusion and exclusion criteria guided by Liao et al. (2017) in their literature review paper.

One of the major steps in SLR research is to choose appropriate search phrases that help to retrieve a wide range of sources. First, we determined which research question had the relevant search terms that can serve as the foundation for conducting our lookup. Second, we found potential synonyms or equivalent phrases for all pertinent topics. Third, we separated the search string using Boolean operators (i.e., AND, OR). Based on the objectives of this investigation, search terms were structured within an established "population" and "intervention" (Kitchenham et al., 2009). In literature reviews, the term "population" usually refers to the application area, in this case, "I4.0," while the term "sustainable innovation" refers to the intervention or exposure. We conducted pilot search with selected keywords. Following piloting, it was evident which keywords resulted in irrelevant documents. For instance, 'I4.0′ is a keyword that appears more frequently in articles than 'Fourth Industrial Revolution'. Based on the results of our pilot search and discussions with the library's information retrieval specialists, we chose the general term "sustainable development" to get diverse types of sustainability aspects such as triple bottom line, circular economy, sustainable development goals, and sustainable business models, among others. The main constructs 'I4.0' 'Innovation' and 'SD' were kept generalized so that the search results are vast enough to be interpreted in many directions. After pilot search string, we obtained following search string to address the research questions based on the scope of this study.

> (Industry 4.0 OR I4.0 OR "smart manufacturing" OR "industry 4.0 technology" OR "smart factory" OR "fourth industrial revolution" OR "smart production")AND (innovation OR "innovative") AND (sustainability OR "sustainable development")

In this SLR, we used three electronic databases, namely Web of Science, SCOPUS, and IEEEXplore, to collect academic research papers. These are the largest pertinent databases related to our research topic and recommended by various researchers (Dybå and Dingsøyr, 2008; Kitchenham and Brereton, 2013). Our search terms focused on article titles and abstracts in order to retrieve as much relevant literature as possible about I4.0 and a mix of sustainability, TBL, CE, SDGs, and SBMs. We found 1432 items in the three databases. The search results were imported into a Microsoft Excel spreadsheet. The retrieved records were filtered in phase 1 based on publication date (1st January 2012–12th June 2022). The literature selection approach employed in this study is depicted in Fig. 1.

In this study, we focused exclusively on journal articles and applied a database level filter to limit our search to specific field topic of study. Through this careful filtering process, we identified 1432 records from three databases. Our initial screening filter was designed to exclude papers that were not relevant to the scope and subject of our research, such as those related to mathematics, material science, physics, chemistry, conference papers, and book chapters. This stage produced 894 items out of 1432 total. The second phase excluded papers based on title, duplicates, non-English and non-scientific content which produced 168 distinct articles (journal articles only). Two authors read 168 papers independently against the goals and objectives of this research using following exclusion and inclusion criteria (see Table 1). Exclusion and inclusion criteria allow the systematic literature review to identify resources that address the research questions (Kitchenham et al., 2009). We defined and used the following "Inclusion/Exclusion" criteria in the context of this study.

Whenever there was a question or disagreement of a specific article, the two authors discussed it and came to an agreement on its inclusion or exclusion criteria. We followed a rigorous screening process to select relevant papers for our analysis. After applying a series of filters to exclude papers that were outside the scope of our research, we found that out of 168 primary records 110 papers did not fully or adequately address the topic of innovation as an outcome in terms of process,

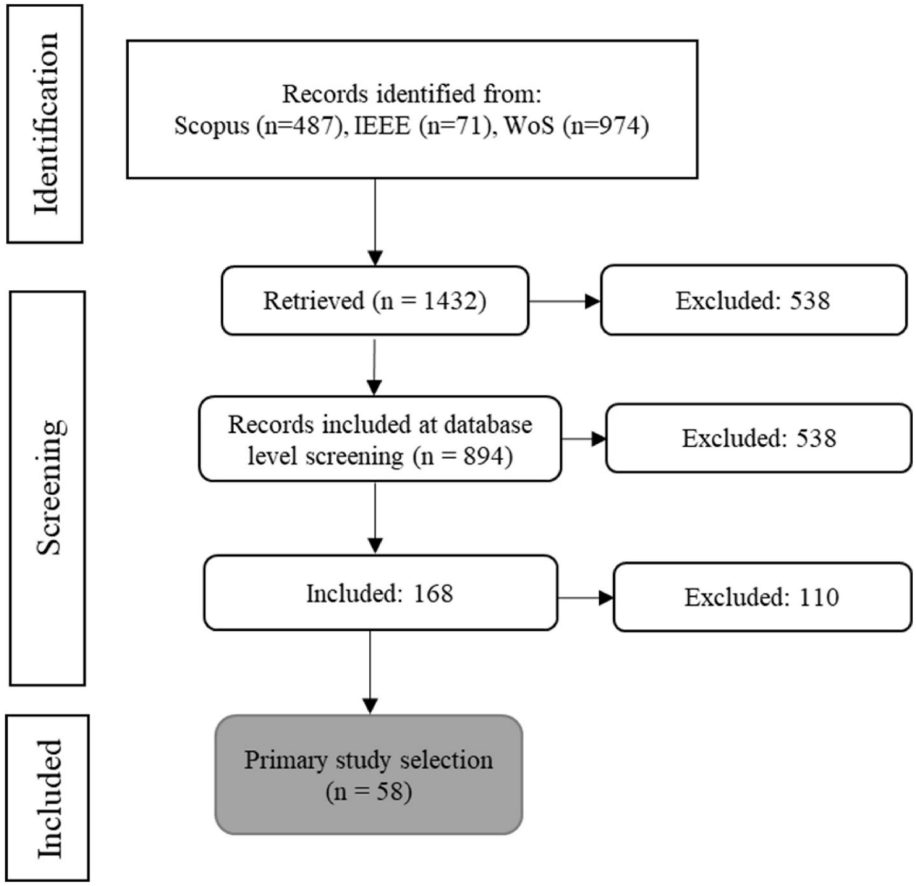

Fig. 1. Literature selection process.

Table 1
Inclusion (I) and exclusion (E) criteria.

I/E	Criteria	Criteria explanation
Exclusion	Language discrepancy	A paper has title or abstract in English but not the full text
	Conference proceedings and book chapters	A paper is not an academic journal article; For instance, conference reviews, book chapters, editorial materials, letters, or forewords
	Non-related articles	A paper does not focus on I4.0, related technologies, resulting innovations and related sustainability implications. In which, 1: I4.0 is just used as an example 2: Innovation is considered as an embedded feature of I4.0 but not as an outcome 3: The innovations do not have further implications for sustainability/SD
Inclusion	Time span	Journal articles published only between 2012 and June 2022 are included
	Related articles (AR)	The relationship of the research constructs should always start from I4.0 (leading to) innovations and SD and not vice versa
	Review articles (RA)	The review articles are exempted from the (AR) condition; meaning that the review articles should be included if it has all the research constructs present, regardless of the relationship flow mentioned above

product, and so on. Thus, these papers were excluded from the final analysis. The final selection of papers for data extraction and analysis consisted of 58 articles. These papers were chosen based on their explicit descriptions and the flow of information stemming from the context of I4.0, resulting innovations, and their sustainability implications. Papers that did not meet these criteria were excluded. For example, papers where I4.0 was only used as an example, innovation was considered as an embedded feature of I4.0 but not as an outcome, or the innovations did not have further implications for sustainability or sustainable development were not included in our analysis. We obtained 58 articles for data extraction and analysis.

All primary studies were thoroughly examined after cautious selection. To eliminate researcher bias, we employed the approach of researcher triangulation and the development of specialized data extraction definitions. All primary studies were assessed for both quality (e.g., research rigor and relevance) and study characteristics (e.g., study type, method, domain, industry type, pertinence, publication channel, sustainability aspects, type of innovation, etc.) proposed by Dybå and Dingsøyr (2008). The key questions in the quality assessment criteria were if a research paper provided adequate description of the study context, data collection and analysis were clear, statement of findings were provided and if it holds the value for research or practice. Two authors assessed each original study separately before including their peer-reviewed findings into the analysis and reporting of workshop settings. This strategy helped authors to discuss and resolve any differences. Finally, one author got a bird's-eye view of the whole SLR as well as each step. It contributed to maintaining analytical uniformity, aggregating results, and disseminating. We focused to establish links between various types of innovations, sustainability and sustainable development, circular economy, SDGs, and sustainable business strategies. These links can be used for integrating disparate knowledge on various types of innovations, which can then contribute towards various aspect of sustainability and sustainable development.

4. Results

4.1. Descriptive analysis

The final dataset of current research contains 58 papers searched available between 2012 and June 2022. The search was limited to 2012 because the term was coined the year before in 2011. Fig. 2 depicts a general increase in the number of publications from year to year. However, our results show that the academic discussion on I4.0 impact for innovation and sustainability together had only started after the year 2016. Since 2019, until the time of this study, the number of publications on our research theme has rapidly increased. This increasing trend in the number of publications shows a growing interest of researchers around this incredibly significant and timely construct of digitalization, resulting innovations and their sustainability implications.

Considering the significance of research methods applied in the papers, we analyzed the trend of various research methods used to explore I4.0 for innovations and sustainability. Fig. 3 reflects that the majority of the literature consists of mixed method studies (n = 15), followed by surveys (n = 12), case studies (n = 10), literature reviews including conceptual papers (n = 10), mathematical modelling (n = 7) and experimentation (n = 2) and simulation articles (n = 2). We combined a mix of qualitative and quantitative approaches used in the article under the theme of mixed methods. The results show that the current research topic gained scholarly attention from qualitative and quantitative perspectives. While the conceptual and review papers have provided an explanation of how I4.0 technologies may affect numerous types of innovations for sustainable development, the case studies contained a general validation of the theoretical concepts along with empirical applications. However, there is a need for experimentation, prototypes and simulation approaches which can help to assess the design problems and propose suitable solutions.

According to the bibliographic distribution, our sample articles are published in 27 diverse sources. Our literature captured the highest percentage of primary studies in Sustainability (n = 20) and Journal of cleaner production (n = 8). There were four primary studies published in Technological forecasting & social change and two articles each in Business strategy and the environment and Energies. The remaining 22 primary studies are published in a wide range of journals. While the findings show diverse types of journals on the domain in hand, it will be interesting to explore common patterns, groups, or characteristics used across journals after some years when the field gets further acknowledgement. The complete list of primary studies venues is shown in Table 2.

Two authors, Ghobakhloo and Garcia-Muiña, each contributed two publications to the review topic, which focused on the investigation of I4.0 and sustainability constructs (See Table 3). Both articles by Ghobakhloo begin with a systematic literature review followed interpretive structural modelling technique to analyze (a) contextual relationships among the I4.0 sustainability functions, and (b) develop a strategic roadmap that explains how businesses can leverage I4.0 technologies to incorporate sustainability into innovative practices. Ghobakhloo (2020) conducts a literature study on the sustainability functions of I4.0, focusing on core design concepts, technological trends, and I4.0 architectural design. The content-driven analysis identified 16 separate I4.0 sustainability functions. The findings show that economic sustainability functions (i.e., production efficiency and business model innovation) are a swift result of I4.0, pointing the way further to socio-environmental sustainability functions (i.e., energy sustainability, harmful emission reduction, and social welfare improvement). Ghobakhloo et al. (2021) then created a strategic roadmap outlining how firms may use I4.0 technology to incorporate sustainability into innovative practices. The findings reveal that I4.0 enhances manufacturing competencies and promotes organizational capabilities relevant to sustainable innovation, increases green process innovation capacity, and reintroduces economic, competitive, and eco-friendly goods.

Garcia-Muiña et al. (2019) analyzed a balancing point between sustainability and circular economy in an I4.0 context and proposed eco-design and Triple-Layered Business Model Canvas as a tool to predict the equilibrium point between sustainability, circular economy and business model transition respectively contributing to all three pillars of sustainability.

4.2. Different types of innovation outcomes of I4.0

While innovation is considered as a pervasive term for I4.0, its identification, categorization, and distribution into distinct innovation types is elusive in the current literature. Recognition of these innovative outcomes is significant to understand the true manifestation of I4.0 and its respective benefits. The results from our selected primary studies yielded different types of innovations which were analyzed based on the output/outcome, as suggested by Kahn (2018) in Fig. 4. A vast number of primary studies address I4.0 from a process innovation (n = 18) perspective focusing mainly on the changes in process pertaining to lowering the costs, increasing efficiencies, speeding processing time to enhance production systems and organizational processes. The results

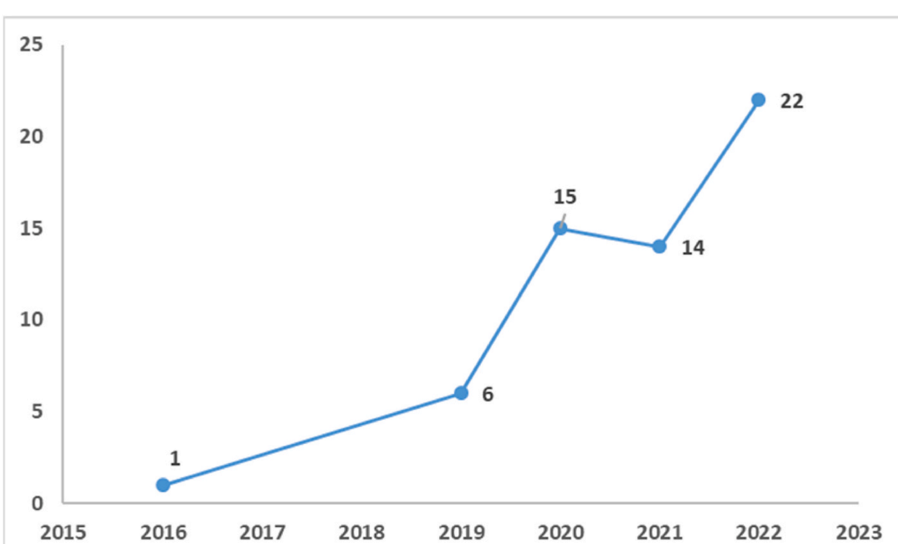

Fig. 2. Distribution of publications over time.

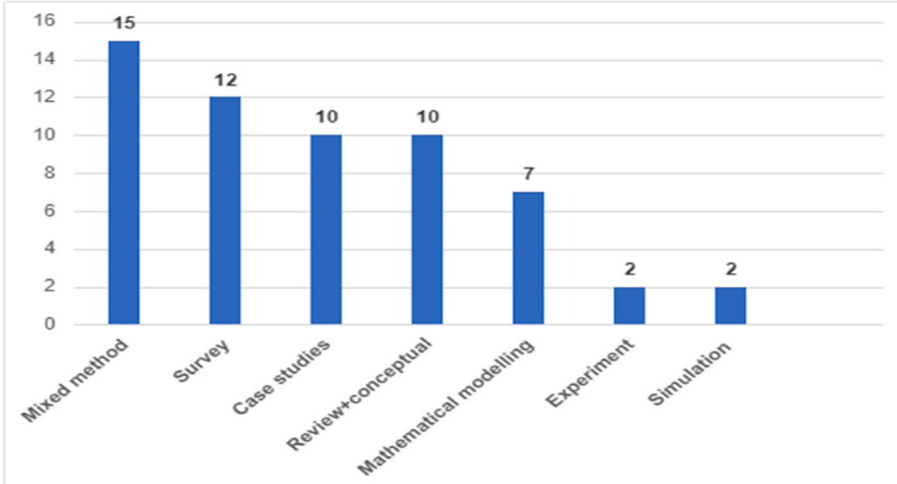

Fig. 3. Research methods used in the studies.

Table 2
Publication channels of primary studies.

Publication Channel	No. of Publications
Sustainability	20
Journal of cleaner production	8
Technological forecasting & social change	4
Business strategy and the environment	2
Energies	2
CIRP Journal of manufacturing science and technology	1
Cogent business & management	1
Computer and industrial engineering	1
Computers in industry	1
Construction innovation England	1
Ecocycles	1
Energy economics	1
Entrepreneurship and sustainability issues	1
Fashion and textiles	1
Global food security agriculture policy economics and environment	1
International Journal of Innovation Studies	1
Journal of ICT Standardization	1
Journal of manufacturing technology management	1
Knowledge management research and practice	1
Management Decision	1
Management of environmental quality	1
Production planning and control	1
Social sciences BASEL	1
Sustainable energy technologies and assessments	1
Technology in Society	1
Technovation	1
Frontiers in Education	1

Table 3
High-contributing authors in the field.

Authors	years	Publication venue	Key research areas
Ghobakhloo et al.,	2021	Business strategy and the environment	Sustainable innovation; I4.0; Digitalization; SD.
Ghobakhloo, M	2020	Journal of cleaner production	Environmental sustainability; Digitalization; I4.0; Smart manufacturing.
Garcia-Muiña et al.,	2019	Social sciences	I4.0; Sustainability; CE;
Garcia-Muiña et al.,	2020	Sustainability	I4.0; sustainable manufacturing; Business models

also show that the literature to date has also reflected well on the I4.0 implications for business model innovation (n = 12) which primarily included changes in the value chain, configuration of new revenue models and changes in the extended networks of the enterprises. The innovation in general category (n = 9) mainly reflects on the adoption and implementation of I4.0 in multifaceted sectors such as, energy, food and agriculture nexus, or economic developments of nations which summarizes that an assessment of each technology and their respective innovation at the junction of distinct sectors and economies will lead to the guiding practices towards cleaner production (David et al., 2022; Zhou et al., 2020).

While the crossover between the product and process innovation is well-known, we categorize both differently by attributing efficiency to reduce cost for the former, whereas development of the new products with added resources to force the changes in manufacturing process for the latter (Kahn, 2018). Despite some commonalities between these two types of innovations, product innovation (n = 6) has comparatively a smaller number of studies, which provides an avenue for further research. The results further show important I4.0 based innovation outcomes, namely supply chain innovation and technological innovations, consisting of 5 papers each in the sample. From a supply chain innovation perspective, the papers widely addressed an innovation caused by I4.0 in the supply chain networks, technologies and processes within an industry or a company, whereas an I4.0 based technological innovations papers comprised of identifying new technological possibilities to organize the sustainable human and financial resources.

In the realm of I4.0 open innovation is another dimension which utilize the latest information and communication technologies to develop new ways of manufacturing products and developing digital services. While the literature has seen a remarkably increasing trend in the number of publications concerning diffusion of digital technologies and open innovation (Strazzullo et al., 2022), our results show that an exploration of the intersection between I4.0 and open innovation for sustainability is still in infancy (n = 4) and therefore requires further attention. We identified two more salient types of innovation, namely organizational innovations (n = 3) in which the papers mainly addressed changes in management, organizational structure and work environment, and marketing innovations (n = 1) in which the papers reflected mainly on connecting customers to new promotional offerings, brand awareness and recognition. However, considering the significance of organizational culture, work environment and customer satisfaction the number of studies reported in the last two categories are exceptionally low and thus needs diligent research. Other studies, mostly review papers approached innovations from a general perspective promoting

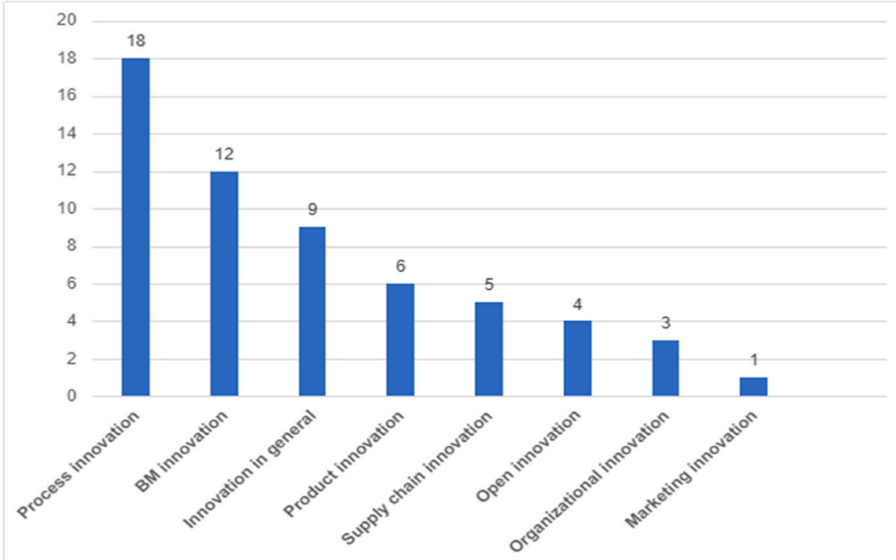

Fig. 4. Different types of I4.0 innovations.

concepts such as education 4.0 for sustainable development (Chaka, 2022), education engineering for innovative skills and SDGs (Muñoz-La Rivera et al., 2020), disruptive innovations for sustainable drugs development (Paulick et al., 2022) and agriculture 4.0 for responsible innovation and sustainability (Klerkx and Rose, 2020).

4.3. Sustainability implications of I4.0 based innovations

As stated earlier in the introduction section, we theorized SD as a multi-dimensional umbrella term (Khan et al., 2021a,b) in current research to incorporate many distinct aspects of sustainability. In combination with I4.0 and innovations, we chose to search broad term of 'sustainable development' and 'sustainability' which resulted in multiple significant constructs used within sustainability paradigm such as triple bottom line, circular economy, business models for sustainability, sustainable development goals and environmental sustainability features (Fig. 5).

While our results show multiple articles addressing the disintegrated sustainability aspects such as reflecting on the social aspects or economic aspects alone, many of the primary studies assessed I4.0 based innovations with respect to all three pillars of sustainability comprising the economic, social, and environmental (TBL) aspects (n = 11). Several studies also focused purely on the environmental implications (n = 9). The results related to most of the papers addressing TBL seem to be justified because the TBL dimension lies at the center of the sustainability paradigm. In addition to TBL, much of the I4.0 based innovations literature analyzed has endeavored an assessment of circular economy (n = 10) and sustainable business models (n = 8) utilizing the principles of reducing, reusing, recycling, recovering, remanufacturing, and redesigning, and features of sustainable value creations for societies and businesses respectively through I4.0 technologies. While the United Nations 17 sustainable development goals (UN SDGs) are considered as a strategic tool to achieve sustainable solutions, our results show that an analyses of the possible contribution of I4.0 and resulting innovations to achieve SDGs (n = 3) is still underdeveloped and requires further consideration for the development of societies. Considering these results, we provide a detailed content and thematic analysis of the interplay between the I4.0 concepts and technologies, in relation to its different types of innovations and a discussion about their further sustainability implications below.

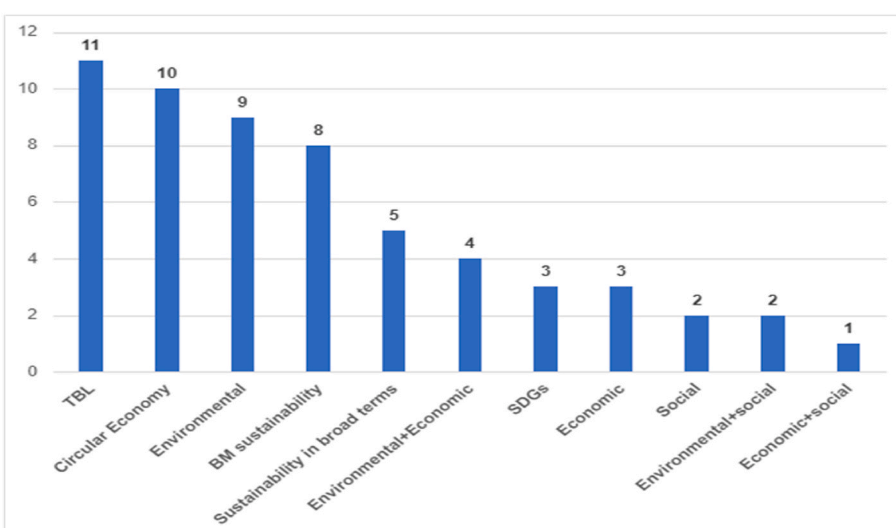

Fig. 5. Sustainability implication of I4.0 innovations.

5. Content and thematic analysis of the I4.0-innovations-sustainability nexus

This SLR investigates the impact of contemporary I4.0 concept and its key technologies not only on the intended and resulting innovations but also their sustainability implications covering several perspectives (Fig. 6). A systematic analysis of these innovations with respect to their ultimate purpose and their crossover for sustainability presents a synthesized clarity on the current studies and future research needs. As I4.0 has proven to bring a remarkable shift in technologies by producing more automatic, reprogrammable, and multipurpose machinery and systems, it has resulted in multitudinous innovations. Additionally, the growing significance of incorporating sustainability into innovation efforts has also gained attention as practitioners in the modern world are required to align sustainability considerations with innovative practices. In the quest to understand the I4.0-innovations-sustainability crossover, this study identifies seven different types of innovation outcomes of I4.0. Our results show that I4.0 technologies, both individual ones and their combinations, lead to several types of innovations (i.e., process, product, business model, supply chain, organizational, open, and marketing innovations) that promote the TBL sustainability, CE, SBMs, and achievement of SDGs. However, as the decreasing width of the connecting arrows represent weak relationship, we propose that more research is needed to examine under-explored areas such as open, organizational, and marketing innovations that support business model sustainability and SDGs. Below, we interpret and summarize each type of innovation in relation to the key I4.0 technologies used, and its distinct sustainability implications followed by the future research directions.

5.1. Process innovation and sustainability implications

Industry 4.0 enhances the organization's productivity by revolutionizing process innovation, thus facilitating and encouraging many new business opportunities (Park and Bae, 2022). With the advent of modern technologies, companies are transforming their production processes not only for the economic benefits, but to invest in environment-friendly innovations which can improve the processes by reducing waste and emissions, managing pollution, supporting recycling, and saving the energy (Sun et al., 2019; Cherrafi et al., 2017; Panda et al., 2017) Thus, enhancing overall environmental performance (Schiederig et al., 2012). This digital transformation is based on technological innovations arising from the application of AI and elucidative engines, such as industrial robots. For example, electrification and automation company ABB has utilized AI in the production planning process and network technology company Nokia uses robotics in its production line in assembly and in-house logistics. Research shows the use of industrial robots to improve technology and energy efficiency mainly in labor intensive work sectors (Wang et al., 2022) and green technology innovation to mitigate climate changes in the production process (Lee et al., 2022) enhancing economic growth and environmental sustainability, respectively. One example of successful digital transformation is the case-study research on medium-sized enterprises carried out by Ondov et al. (2022) which shows the development of a production process model by installing I4.0 based automation. The results not only condensed the production process but also decreased environmental emissions and energy consumption. Furthermore, the significance of I4.0 for process innovation leading to sustainability is empirically studied which reveals that I4.0 technologies tend to develop the architectural design of organizations which promote the TBL functions of sustainability such as production efficiency, emission reductions and social welfare and work improvement (Ghobakhloo, 2020; Braccini and Margherita, 2018) in addition to positive influence on the business performance for the large companies (Jin and Choi, 2019) thus promoting organizational sustainability (Nasir et al., 2022).

Integration of digital technologies with CE principles is considered another fundamental discourse to accelerate a company's innovation processes and competitive advantage both in academia and practice. Car manufacturers, such as Renault, are already using reuse, remanufacture and recycle principles to utilize the value of end-of-life vehicles and their components. Digital diagnostics combined with digital data on vehicle and component use history improve the efficiency of the take-back process and make CE models even more attractive in the automotive industry. In our review sample De Mattos Nascimento et al. (2022)

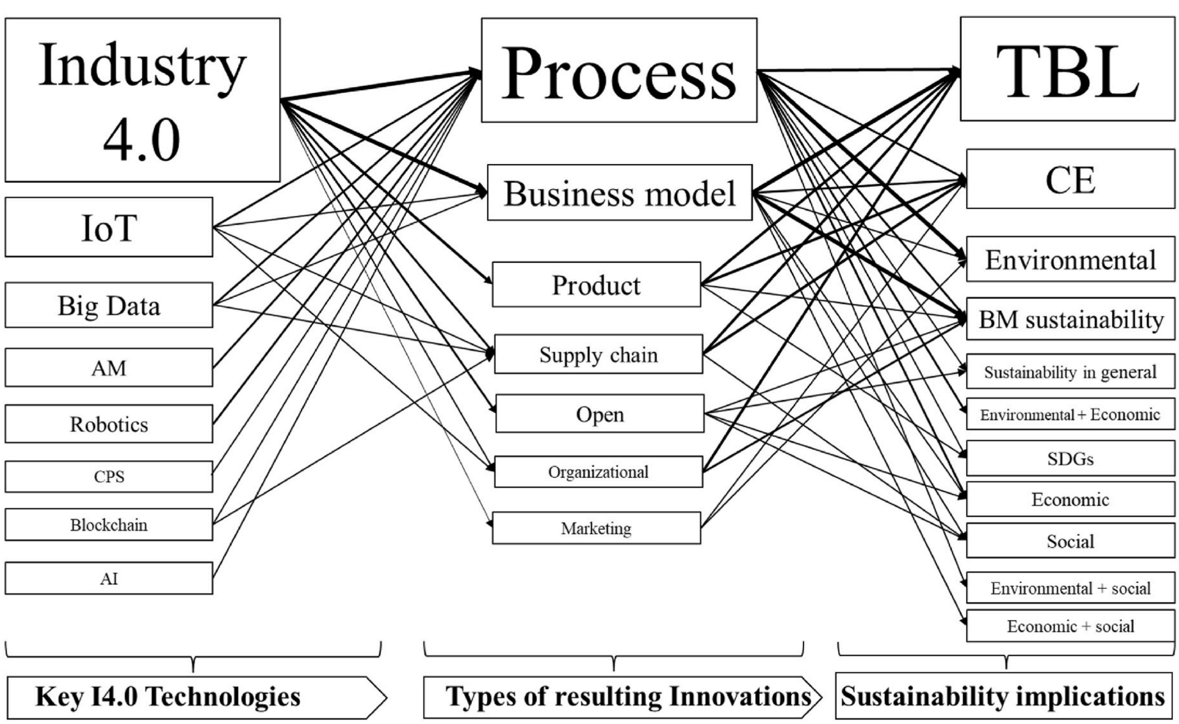

Fig. 6. Thematic illustration of Industry 4.0 resulting innovations and their sustainability implications.

utilized 3D printing and introduced a CE based approach for smart production which can take the waste back and use it as raw material with an on-demand manufacturing feature for recycling that improves social and environmental sustainability. Dixit et al. (2022) connected the relationship between lean manufacturing and ambidextrous innovations processes and labelled IoT as a tool to minimize costs as well as reduce the waste in the relationship, whereas Dahmani et al. (2021) extended the relationship to reuse, reduce, recycle (3R) perspective. While taking the debate to a regional level, Borowski (2021) analyzed I4.0 solutions together with innovation strategies and proposed them as key to reduce energy consumption and environment protection for EU. An experiment-based study also presented the advantages of 3D printing for mass customization improving construction efficiency and cost reduction which ultimately led to minimize the construction waste and support the use of recycled products (Tahmasebinia et al., 2020) enhancing technological, environmental, and social aspects (Iuorio et al., 2019), and in prefabricated building sector promoting TBL and SDGs (Gallo et al., 2021).

As our results show there is limited research on I4.0 based innovations to achieve SDGs. Oláh et al. (2020) proposed that to overcome the challenges in the flow of production process, the integration of I4.0 and SDGs can enhance the negative relationship between the inputs and final product thus promoting environmental sustainability. Regarding process innovation, other studies indicated specific technologies such as IoT and BD boosting the efficiency of eco-innovations as well as socio-economic performances of the companies (Tumelero et al., 2019; Munodawafa and Johl, 2019), promoting the use of knowledge-based systems for innovative and environment-friendly farm infrastructure (El Mehdi Ouafiq et al., 2022), precision farming for waste reduction in agriculture sector (Takács-György and Takács, 2022), modelling design for the port of the future contributing to environmental sustainability (Pagano et al., 2022) and industrial robots optimizing the production structures and reducing carbon intensity (Li et al., 2022). However, more detailed, and comprehensive studies are needed to evaluate the determinants of the firm's overall innovation performance needed for organizational sustainability (Jin and Choi, 2019).

5.2. Product innovation and sustainability implications

I4.0 as an underlying concept and its respective technologies have shown a significant impact to innovate the machinery producing the finished or in process products. Different types of connected sensors are installed in factories and embedded in products to ensure smooth operations and extend the lifetimes. Rolls-Royce jet engines are one of the most famous examples of this. I4.0 technologies can enable trouble-free operation and smart maintenance that also enable Rolls-Royce to provide "power-by-the-hour" type of offering to airline companies. Eco-innovation embedded with IoT functions can enhance the design phase of the products and extend their lifecycles thus promoting circular business models as an operational tool for TBL benefits and enterprise profitability and competitiveness (Garcia-Muiña et al., 2019; Tumelero et al., 2019; Dahmani et al., 2021; Jin and Choi, 2019). More specific technologies such as additive manufacturing is identified as capable of re-thinking and re-designing the products, thus extending the life of the product bringing repair operations forward which contributes to the essential principles of CE (Priarone et al., 2021). These technologies carry the potential for mass customization of products and transforming them into smart and sustainable products with minimal waste and low environmental impact resulting in business model sustainability (Murmura et al., 2021). However, the continuously evolving technological innovations and their rapid disseminations are radically changing the entire value chain of businesses which suggests a need for the analysis of the whole value chain starting from designing the product to its delivery to the end customer.

5.3. Business model innovation and sustainability implications

I4.0 posits several opportunities for the companies to revisit their traditional and linear business models to more innovative and sustainable business models. In this regard, Wit et al. (2021), García-Muiña et al. (2020) and Gerlitz (2016) proposed the integration of sustainability thinking and design integration for the development of sustainable business model innovation architecture which operates as value proposition to meet the TBL needs of the society. In addition, Kurniawan et al. (2022) presented a business model transformation of waste industry which encourages the local community to sell waste through an app. This transformation adds economic value to recycle waste using digital technologies, which not only promotes the resource recovery mechanism of non-biodegradable waste for a CE, but also supports social innovation for sustainable local community.

As sustainable business models aim to develop environmental and societal-friendly business, Todorović et al. (2022) and Pasqualino et al. (2021) analyzed the determinants of smart and sustainable public parking enterprise and a system dynamic model for sustainable innovations respectively and presented social and business model sustainability as outcomes based on intelligent technologies. Some of the determinants to successful business model transformation for innovation, sustainability and CE highlighted are product as service model (Han et al., 2020), manufacturer's knowledge about technological readiness and managerial maturity and personalized production systems which can enhance efficiency, productivity, unmatched demand and oversupply problems, co-creation and collaborative approaches and customer experience throughout the value chain contributing to environmental and organizational sustainability (Ching et al., 2022; Jin and Shin, 2021; Pereira et al., 2022; Ng et al., 2021; Lardo et al., 2020). Especially, with a careful assessment of technological readiness, a wider set of businesses can enhance their environmental management, CSR, and CE practices (Kazancoglu et al., 2021). As a future research direction for BM researchers, Rao (2021) highlighted the significance of BD to be used in organizational innovation processes and proposed future research on sustainable businesses through data-driven business model innovations.

5.4. Supply chain innovation and sustainability implications

I4.0 is largely characterized to bring increased adaptability, efficient resource usage, cost effectiveness and integration of customers and business acquaintances for ecological, economical, and societal gains in the supply chain context (Fallahpour et al., 2017). I4.0 technologies, such as BD have empirically shown their potential to improve the analytical capabilities and employee empowerment, development, and involvement to enhance supply chain innovation and sustainability performance, specifically highlighting social sustainability (Jaouadi, 2022). For example, the world's largest container shipping company Maersk has utilized an AI-assisted container packing system to improve efficiency in logistics and decrease the costs. Already the first trials resulted in a 9% increase in efficiency in the container packing. Mastos et al. (2020) developed IoT solutions, such as automation and monitoring procedures for the scrap metal resulting in less carbon emissions, availability of resources and optimization of response time, thereby supporting the TBL sustainability in supply chains.

Contributing to the CE paradigm, Chang (2022) connected knowledge management innovation model with 'reduce' function of CE to illustrate smart production with less chemical emissions and raw materials and hence to promote the concept of green/sustainable supply chain innovation. Similarly, Rossi et al. (2020) analyzed the enhancement of CE coupled with the intelligent I4.0 assets throughout the supply chain including product design to product utilization and novel business strategies to extend the product life cycle. While Kouhizadeh et al. (2020) linked the blockchain technology for CE transformation within the supply chain, they suggested the use of ReSOLVE framework based on regenerate, share, optimize, loop, virtualise, and exchange dimensions for future research.

5.5. Organizational and marketing innovation and sustainability implications

While organizational innovation is associated generally with the organizational culture, I4.0 tend to address it through a shift of the skilled workforce, sustainability in corporate governance, leadership and change in organizational culture and customer relationships (Fan et al., 2021). For example, consumer goods company Unilever has improved its employee experience with digital solutions that simplify and optimize human resource services and make employees more engaged with the organization. A careful evaluation and adoption process of the right I4.0 strategy with respect to organization's internal forces hindering the implementation process can result in new innovations which further gain sustainable competitive advantage (Ramadan et al., 2022). Moreover, I4.0 implementation in small and medium sized enterprises (SMEs) designed in compliance with corporate social responsibility (CSR) principles, such as the use of cleaner production and CE concepts, can enhance the organizational innovation strategies and overall performance which further augments exploration of sustainable business model development with improved environmental management practices, circular product design for enhanced market performance (Pinheiro et al., 2022) and efficient production systems for social sustainable development (Lu et al., 2020).

5.6. Open innovation and sustainability implications

The existing literature makes limited contributions to understanding the influence of I4.0 on the underlying mechanisms and enabling capacities of sustainable innovation (Mubarak and Petraite, 2020). One of the key issues companies are now facing in adopting a digital approach is identifying, selecting, and execution of tailored digital strategies that align with the organizations' innovation initiatives (Sjödin et al., 2018). Companies may use open innovation to build successful systems for involving or "hooking" external collaborators into their internal operations (Strazzullo et al., 2022; Bugshan, 2015). Digital tools are helping information flows that emerge during open innovation processes and have contributed to the change toward the adoption of practices based on open innovation (Dodgson et al., 2006). For example, Google organizes various types of hackathons and provides a crowdsourcing platform that supports the principles of open innovation. Furthermore, I4.0 technologies help to overcome the value-creation challenges for open innovation which enable a smooth transition towards sustainable society focusing specifically on social and global well-being (Aquilani et al., 2020), and provide grounds for networks and high-paced innovation cycles harnessing the regime of innovation ecosystems (Costa and Matias, 2020). These contributions underline that academic discussion has been more focused on digital technologies that support the inbound open innovation process. In summary, the paradigm of open innovation is playing a key role which creates a need to do more research on the proliferation and adoption of enabling technologies leading to sustainable development.

6. Future research directions

Our study identified several gaps in the existing literature that provide opportunities for future research. Regarding I4.0 and the use of specific technologies, blockchain, for example, is a key technology that can enable new CE solutions. Thus, it is one of the topics that require more research in the future. Overall, future research is required to investigate the impact of distinct types of I4.0 technologies that result in new innovations, with special attention towards market and performance evaluation features. For instance, it will be interesting to investigate the way industries reduce their costs and improve their time to market with respect to new technological innovations.

Incorporating sustainability considerations into organizations' process and business model innovation efforts is important and requires, for instance, analysing the extent to which this type of integration impacts overall organizational performance and purpose (Müller, 2019). Connected research direction to this can be assessing the implementation of CE business models in relation to certain sustainability outcomes, such as reducing waste and resource consumption, and increasing economic efficiency. We also highlight the need to study significance of behavioural factors within organizations, such as an assessment of how process and business model innovation can change the organizational culture and behaviour towards sustainability. Future research is also needed to explore and compare different types of markets and supply chains in a range of organizations, such as SMEs and large multinational corporations. This can also help organizations not only focus on improving their processes but also explore new ways to sustainably innovate in their specific contexts, hence enabling novel thinking and achieving coevolution and complementation of diverse types of innovations, simultaneously.

Considering the complexity and diversity of sustainable development and the substantial number of stakeholders whose needs must be addressed in it, it is evident that more research is needed on how organizational and marketing innovations for sustainability can be advanced, as well as how open innovation can be utilized for creating sustainability innovations. For instance, a missing aspect, specifically from the marketing innovation perspective is lack of focus on research and development (R&D) activities. As R&D lies at the core of technological innovations (Fujii and Managi, 2019) this is an area that needs more attention in the organizations in the future. While the research has focused on culture and strategy aspects in organizational innovation, further research is needed to investigate the implications of I4.0 based innovations to human resource management, knowledge transfer among employees and related stakeholders, as well as teamwork and talent management contributing to twin transition which embrace innovation and sustainability at the same time.

As the businesses seek a growing interest in utilizing open innovation at the process level, more research is needed to examine how diverse types of open innovation strategies and the combination of inbound and outbound open innovation processes can be applied across various business sectors (Strazzullo et al., 2022). In line with Adamides and Karacapilidis (2020) who highlighted the crucial role of information technology in fostering and sustaining open innovation capability, with a specific focus on collaboration and advanced data analytics, we propose to explore how digital platforms can be designed to support collaboration among a diverse group of stakeholders and how digital technologies can be used to manage and track the progress of open innovation with respect to sustainability outcomes and global circularity. Furthermore, it would be interesting to investigate the financial and non-financial benefits of open innovation for sustainability and how these benefits can be leveraged to drive organizational change and future innovation initiatives. Thus, it is obvious that especially social aspect of sustainability is still a significant gap in I4.0 innovation literature and calls for further research in the future.

Furthermore, in the context of I4.0, there is limited research on socio-environmental aspects of sustainable development at the macro-regional scales. In this regard future research is needed from three aspects. Firstly, empirical investigations are needed in various areas such as corporate inequality, income inequality, digital divide, rebound effect, among others. Secondly, further research is needed on policy level assessment and economic trends on I4.0 sustainability. Thirdly, longitudinal studies are required to measure the long-term sustainability impacts of individual I4.0 technologies while also taking into consideration I4.0 complexity and externalities (El Baz et al., 2022). In addition, future research on social and environmental sustainability aspects could focus on: (a) examining how organizations can effectively incorporate social and environmental sustainability goals into their overall business strategy and how this integration impacts organizational performance, (b) assess the effectiveness of different sustainability reporting frameworks (i.e., Global Reporting Initiative, Sustainability Accounting Standards Board) to promote social and environmental sustainability outcomes; (c) explore how different technological innovations, such as IoT and blockchain, impact social and environmental sustainability outcomes differently (d) highlight the differences based on technological implementations for sustainable innovations in developed and emerging economies, or at different organization types, such as SMEs and multinationals.

Regarding CE and I4.0 future research needs to focus on how I4.0 technologies can properly support customers and suppliers involved in circular business models, as well as investigate the potential impact of I4.0 technologies in designing circular business models. The implementation of digital CE requires continuous monitoring of the materials and products' entire lifecycle, which can be enabled through I4.0 technologies. Based on our review, we can also conclude that studies on I4.0 innovations with sustainability implications have mostly focused on the manufacturing sector. Only a few studies have been conducted on other sectors, which leaves a space for further research in different industries including, for example, electrical and electronic equipment and pharmaceutical sectors.

At the end, we would recommend utilizing and adapting some of the existing models and frameworks for a comparative analysis of I4.0 readiness, adoption, and implementation in both developing and developed countries. These models include BD analytics and human resource factors' impacts on supply chain innovation (Jaouadi, 2022), contextual relationships among the I4.0 sustainability functions (Ghobakhloo, 2020) and relation between the introduction of eco-innovations and socioeconomic performance of companies (Tumelero et al., 2019).

7. Conclusion, implications, and limitations

Our study applied systematic literature review method to analyze the I4.0-enabled innovations and how they impact different aspects of sustainability and sustainable development. Overall, the results show that research on I4.0 innovations and their sustainability implications are growing. I4.0 can be seen as a holistic concept, so it is somewhat natural that the previous studies have mostly focused on I4.0 concept implementations with a combination of different technologies. However, only a few studies have focused solely on innovations that have resulted from individual technologies, such as IoT, machine learning (ML), artificial intelligence (AI) and blockchain. Furthermore, our results demonstrate that process and business model innovations are by far the most studied I4.0 innovation types which leaves the lowest number of studies related to organizational innovation, open innovation, and marketing innovation. From the research methods perspective, most studies have utilized mixed methods, surveys, and case studies, as well as review and conceptual research. Only some studies have applied mathematical modelling, and there is a distinct lack of studies that use experimental methods, such as simulation and prototyping, which provides significant opportunities for future research and designing new innovative concepts to advance sustainability in organizations and value networks.

7.1. Implications

The theoretical contribution of this study demonstrates a broader-level analysis of I4.0 in relation to distinct innovations and their sustainability implications, mainly delivering value for the manufacturing sector. While our results show that the literature to date focuses on the elements of cost reduction and increase in efficiency pertaining to process innovation and revenue generation and network relationships related to new business models based on I4.0, we suggest practitioners to focus on aligning sustainability thinking to their corporate purpose and therefore, examining how organizations can effectively incorporate sustainability considerations into their process and business model innovation efforts. In addition, as we outline the number of changes I4.0 brings to companies in terms of modern technologies, innovations, and business models, it necessitates the practitioners to consider the adaptation elements of organizational culture. Moreover, our results show a comparatively small number of studies related to product and supply chain innovation. As the significance of I4.0 technologies is known to improve the eco-efficiency of business processes, production technologies, and supply chain interactions, a careful analysis of the extent to which these innovations interplay with each other will guide practitioners to choose the best innovative practices according to the varying range of manufacturing contexts (Garcia-Muiña et al. (2020).

Regarding sustainability implications, the I4.0 innovations studied in our sample have mostly resulted in TBL, CE and environmental, as well as SBM implications. Only a few studies have reported and analyzed SDGs, social and combinations of environmental-social and economic-social sustainability implications. Overall, it can be concluded that I4.0 innovations can advance more sustainable practices, but it bounds practitioners to consider the social and environmental sustainability aspects, when new processes and business models are designed, and changes are introduced in supply chains and products. In addition to modern technology adoption, managers are constantly facing pressure from stakeholders to integrate sustainability concerns. Our research provides a synthesized illustration of I4.0-innovation-sustainability trio, which can assist managers in identifying and comparing the most common patterns adopted to date and simultaneously guide about the best practices for the future.

7.2. Limitations

While this work contributes to related research in the field, it also presents few limitations. First, the journal articles studied in this paper are extracted from three databases, which bring forward the limitation of neglecting some articles indexed in other databases. Second, the search terminologies used in this paper may also overlook certain research studies of impact. Third, our results showed that most of our sample articles are studied with a focus on manufacturing sector, which convey the generalizability challenge. Finally, while the aim of keeping the SD term broad was to cover as many aspects of sustainability as possible, the findings may not encompass all the related sustainability implications of I4.0 innovations.

CRediT authorship contribution statement

Iqra Sadaf Khan: Conceptualization, Methodology, Visualization, Formal analysis, Writing – original draft. **Muhammad Ovais Ahmad:** Visualization, Methodology, Formal analysis, Writing – review & editing. **Jukka Majava:** Supervision, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.137006.

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