Industry 4.0 and sustainable development: A systematic mapping of triple bottom line, Circular Economy and Sustainable Business Models perspectives

Iqra Sadaf Khan a,*, Muhammad Ovais Ahmad b, Jukka Majava a

a Industrial Engineering and Management, Faculty of Technology, University of Oulu, P.O. Box 4610, 90014, University of Oulu, Finland
b Department of Mathematics and Computer Science, Karlstad University, Sweden

ABSTRACT

Industry 4.0 has been identified as a major contributor to the era of digitalisation. Its implications for sustainable development have gained widespread attention from the perspectives of the triple bottom line, sustainable business models and circular economy. The purpose of this paper is to map the broad field of sustainable development and investigate the key research areas which comprise the aforementioned perspectives under Industry 4.0 framework. A systematic mapping review was conducted by searching five databases for relevant literature published between January 1, 2012 and April 17, 2020. The search yielded 4291 papers of which 81 were identified as primary papers relevant to the research herein. The primary findings are that the majority of sustainability research focuses on conceptual analysis, and the Internet of Things is dominantly cited with an emphasis on achieving the triple bottom line benefits. Sustainable development in the Industry 4.0 context contributes to circular economic objectives by achieving social, economic, and environmental benefits. Triple bottom line studies mainly focus on Industry 4.0 adoption and implementation, sustainable supply chains, smart and sustainable cities, and smart factories. Circular economy and sustainable business models as emerging research themes that focus on Industry 4.0 adoption and implementation, as well as sustainable supply chains. Our analysis consolidates emerging research patterns areas in both the Industry 4.0 and sustainability literature. Furthermore, it identifies salient research gaps and suggests future research.

© 2021 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Contents

1. Introduction .................................................................................................................. 2
2. Background .................................................................................................................. 3
3. Methodology ................................................................................................................ 4
   3.1. Planning .................................................................................................................. 4
   3.2. Conducting .............................................................................................................. 4
4. Results ......................................................................................................................... 6
   4.1. Publication year ...................................................................................................... 6
   4.2. Publication channel ................................................................................................. 6
   4.3. High-contributing authors ..................................................................................... 6
   4.4. Publication’s country of origin .............................................................................. 6
   4.5. Research methods used in primary studies .............................................................. 6
   4.6. Key technologies ..................................................................................................... 6
   4.7. Key sustainable development themes .................................................................... 9
5. Inter-related themes under sustainable development .................................................. 9

* Corresponding author.
E-mail addresses: iqra.khan@oulu.fi (I.S. Khan), ovais.ahmad@kau.se (M.O. Ahmad), jukka.majava@oulu.fi (J. Majava).

https://doi.org/10.1016/j.jclepro.2021.126655
0959-6526/© 2021 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
1. Introduction

The modern world is concerned with the emergence and use of Industry 4.0 (I4.0); a modern manufacturing system driven by information technology (IT) and achieving sustainable society. In manufacturing, I4.0 has brought new technologies that deliver maximum outputs using effective resource utilisation (Kamble et al., 2018). Cyber-physical systems (CPSs), the Internet of things (IoT) and other recent technologies open pathways for industrial development that enable improved productivity and efficiency in various organisations. According to Tjahjono et al. (2017), I4.0 incorporates big data (BD), IoT and artificial intelligence (AI) for leveraging manufacturing operations. The potential of I4.0 is thus remarkable for achieving sustainable industrial value creation across social, economic, and environmental dimensions by improving resource efficiency (Sharma et al., 2020). The concept of sustainability in the I4.0 context challenges traditional approaches to problem solving and demands more systemic ways of addressing change. This means that the current progression of sustainability and green economies requires a shift from homogenic systems of ‘doing things better’ towards holistic systems of ‘doing better things’ (Sterling, 2004; McKibben, 2007).

The definition of sustainable development (SD) has a broad spectrum characterizing human progress (Brown et al., 1987), resource utilisation (Mieg, 2012) and business interactions (Strandhagen et al., 2017). According to Elkington (1998), sustainability consists of three pillars: social, economic, and environmental. These pillars constitute the triple bottom line (TBL), the objective of which is to meet the resource needs of current and future generations without hampering the environment. Stock and Seliger (2016) suggested that I4.0 holds great potential in grasping sustainable industrial value creation in the TBL. Furthermore, sustainable business models (SBMs) encompass the TBL and account for multiple parties alongside the environment and society at large (Bocken et al., 2014). They are essential in directing and implementing innovative business processes for sustainability by adopting circular economy (CE) strategies such as narrowing, slowing and closing the resource loop (Geissdoerfer et al., 2017), making them key drivers of competitive advantage (Bocken et al., 2014) and overall SD.

Despite the widespread significance of I4.0 as an enabler of SD (Beier et al., 2017) there are limited reviews that have assessed I4.0 from a sustainability perspective (Sharma et al., 2020). This signal that the crossovers between I4.0 and sustainability paradigms remain underdeveloped (Jabbour et al., 2020; Kiron and Unruh, 2018; Fisher et al., 2018). For instance, some researchers discussed I4.0 and its related technologies with respect to TBL and circular manoeuvres (Asiimwe and de Kock, 2019; Jabbour et al., 2020; Nobre and Tavares, 2017; Ribeiro et al., 2020; Alcayaga et al., 2019; Rosa et al., 2020; Odwańczy et al., 2018) while others discussed its sustainable industrial value creation (Kuo and Smith, 2018) by providing ways how societies, businesses and environments interact altogether (Strandhagen et al., 2017) through SBMs (Machado et al., 2020; Tirabeni et al., 2019). However, the analysis of these studies reveals that they interact at the interface of only two or three out of four topics (I4.0, TBL, CE, SBMs, see Table 1). This means that extant literature reviews do not present a wider understanding of I4.0 for SD relating to, the considerable connections of these inter-related subject areas, along with their magnitude which requires further attention (Birkel and Müller, 2021). The reasoning for a further literature review is therefore the broadness of the topics; I4.0 for SD consisting of TBL, CE and SBMs as most studies lack a broader analysis of the concepts that contribute to SD, and they have not analysed the literature to identify existing and emerging interconnected themes or dominant research areas in which both I4.0 and SD are studied. Moreover, to characterize the broadness of these topics, we use systematic mapping research to review rather than a typical systematic literature review (SLR). We chose systematic mapping review as it aims to develop wider understanding of concepts, general research trends (e.g., publication trends over time, research methods and publication outlets), identify knowledge gaps, and classify the sub-sets of knowledge clusters (James et al., 2016; Petersen et al., 2015), which fits to the exact scope of this research.

To map the field around mentioned scope, we formulate six research questions (RQs), as no analogous SD mapping research exists: (1) Who is working in the I4.0-based SD research field and where? (2) What key investigative research methods are being adopted in the field? (3) Which technologies currently address SD needs in an I4.0 context? (4) To what extent are key research themes in SD and I4.0 studied? (5) What are the interconnecting themes in I4.0-based SD research? and (6) What are the current SD research gaps and opportunities based on I4.0? To answer these questions, this paper presents a holistic research approach and positions SD as an umbrella term encompassing TBL, CE and SBMs with the aim of providing researchers and practitioners with a comprehensive understanding of existing and emerging research trends, as well as highlighting research gaps for future research.
Investigating these inquiries is timely, as doing so will generate an understanding of what SD concepts are being applied and thereby support the development of the I4.0 agenda.

This paper is organised as follows: Section 2 introduces a brief primer on I4.0 and SD, including their definitions and how SD is framed in this paper. Section 3 outlined the employed review methodology—that is, systematic mapping. We then present the review findings in Sections 4 and 5; the former section describes patterns and trends and later provides a detailed theoretical discussion based on findings. Section 6 suggests future research directions, while Section 7 concludes the paper and summarises its contributions. Appendix A lists all primary studies used in the current review.

### 2. Background

Sustainability in any form can help establish optimal conditions for tackling 21st-century issues in business and the environment among others (Greenwood and Holt, 2014; Pearce, 2008). According to the Brundtland Report (1987), ‘the concept of sustainable development does imply limits — not absolute limits but limitations imposed by the present state of technology and social organization on environmental resources and by the ability of the biosphere to absorb the effects of human activities’. The Brundtland Report (1987) provides a well-known broad definition of SD as ‘development that meets the needs of the present without compromising the ability of future generations to meet their own needs’ (Diesendorf, 2000). This means that, in addition to a wide range of environmental concerns, SD addresses diverse and complex challenges that change alongside human societies and natural ecosystems around the globe (Robert et al., 2005).

The concepts of sustainability and SD have gained worldwide attention due to their proposed solutions (Olawumi and Chan, 2018) for problems related to the environment, energy, climate change and rural development, among other things (Axelsson et al., 2011). Norton (2005) considers sustainability and SD as synonyms and uses them interchangeably, while Axelsson et al. (2011) claim that the two concepts are rather distinct. The latter research stream describes sustainability as a conceptual term (Ekins et al., 2003) and as a policy vision to prevent the depletion of natural resources (Axelsson et al., 2011) and addresses issues pertaining to biodiversity, conservation and ecological integrity (Ramakrishnan, 2001). In contrast, Sartori et al. (2014) define SD as a multidimensional collective societal process that involves multiple interested parties (Axelsson et al., 2011). Our study describes both concepts as a ‘social learning and steering processes’ (Lee, 1994) where sustainability acts as a discourse or process for achieving SD goals (Sartori et al., 2014).

The most current and relevant interpretation of SD is the triple bottom line (TBL) (Elkington, 1998). The TBL entails three pillars: economic sustainability, which aims to secure liquidity and ensure profit (Schulz and Flanigan, 2016); social sustainability, which contributes to the development of human and societal capital; and environmental sustainability, which refers to the consumption of those resources that can be reproduced from living and non-living things (Hubbard, 2009; Norman et al., 2004). Further, there is growing research about CE as an SD tool for meeting society’s interests at the macro level (Sauvé et al., 2016; Geng and Doberstein, /C19). CE is known as an emerging mindset that aims for the sustainable use of natural resources (McDowell et al., 2017), necessitating a shift from the linear model of ‘take, make, use and dispose/waste’ to the circular model of ‘reduce, reuse, recycle, recover, remanufacture and redesign’ (Jabbour et al., 2020).

While the concept of a typical business model as an abstract representation is limited to value flow within an organization, the

### Table 1

Comparison of related literature reviews.

| Authors          | Years Included | Sources of Primary Studies | Databases                                      | Research Purpose                                                                 | I4.0 and Sustainability Focus                        |
|------------------|---------------|----------------------------|------------------------------------------------|--------------------------------------------------------------------------------|----------------------------------------------------|
| Ku and Smith     | 1990–2017     | Review papers              | EBSCO, SpringerLink, Wiley Interscience, ScienceDirect, Emerald Insight, Open Access Journals | Assessing technological progress towards sustainability (particularly environmental sustainability, mainly through eco-innovation) | Eco-innovation-based technologies targeting TBL sustainability |
| Jabbour et al.   | 2015–2019     | Journal articles           | Scopus                                         | Determining the implications of BD on sustainable supply chain management | BD in supply chain management for TBL sustainability |
| Rosa et al.      | 2000–2018     | Formal and informal literature (including books, scientific reports and industrial reports) | Scopus, Web of Science | Defining the relationship between I4.0 and CE and their reciprocal effects on a company’s overall performance | I4.0 and CE |
| Machado et al.   | 2008–2018     | Journals and conference articles | EBSCO, Web of Science, Science Direct, Scopus | Analysing how different technologies have been used to address sustainable operations while linking them to different guidelines driven by government programs for I4.0 implementation | I4.0 and sustainable manufacturing/operations leading to the TBL |
| Ribeiro et al.   | 1998–2018     | Only journal articles      | Scopus, Emerald Insight, EBSCO, Web of Science | Exploring the literature on additive manufacturing and its impact on TBL dimensions | Additive manufacturing for life cycle analysis resulting in TBL sustainability |
| Asimwe and de Kock | 2014–2019    | Scientific literature      | Scopus                                         | Examining the extent to which concepts of I4.0, sustainability, and socio-technical systems have been jointly considered in the literature | I4.0 and socio-technical sustainability |
| Tirabeni et al.  | 2011–2018     | Journals and conference articles | Scopus, Web of Science | Exploring I4.0 and its recent developments by investigating the complementarity and interconnections among work environments, business and organisational models, and educational approaches | I4.0 and SBMs for organisational and social sustainability |
| This study       | 1st Jan 2012 – 17th April 2020 | Scientific literature and journal articles | Scopus, Web of Science, ProQuest, IEEE Explore | Systematically analysing the I4.0 research landscape with respect to different aspects of SD, mainly concerning the TBL, CE and SBMs | I4.0 and sustainable development; a systemic and synthesised concept of the TBL, CE and SBMs |
abr and thematic analysis of literature about a given topic. Our systematic mapping review process consisted of three phases: planning, conducting and documenting.

3.1. Planning

The first step was defining and clarifying the object (i.e., domain topic) and boundaries of the study. This was difficult to apply to the concept of sustainability not only because the topic is broad, but also because recent years have seen more and more science and engineering fields define a number of niche sustainability-related concepts (e.g., SD, sustainable value, sustainable orientation, flourishing/strong SBM), leading to semantic confusion. Considering our goal of exploring and categorising new SD trends and applications, we decided to only consider studies referring to sustainability in an I4.0 context. Therefore, our review included several types of sustainability and I4.0 articles related to TBL, CE and SBMs. The review covered literature concerning these topics that were published between January 1, 2012 and April 17, 2020. We chose 2012 as the starting year because the term ‘I4.0’ was first publicly introduced at Hannover Fair in 2011.

3.2. Conducting

To conduct a literature search and obtain relevant articles, we defined a search strategy and data sources. Search strings were developed based on the scope of this study and were framed within an established ‘population’ and ‘intervention’ (Kitchenham et al., 2011). In literature reviews, a population refers to the application area, which in this case is ‘I4.0’, while the intervention or exposure is ‘sustainability/SD’. We ran a pilot search on our selected keywords. After piloting, it became clear which keywords produced noise or irrelevant papers. For example, most of the articles use ‘I4.0’ as a keyword compared to ‘Fourth industrial revolution’. Based on our pilot search and consultations with the library information retrieval experts, we took ‘sustainability’ as the umbrella term covering TBL, among other things. The piloting also helped exclude the ‘cleaner’ production keyword because it yielded many hits related to chemistry, chemical processes and other scientific articles, which were out of this study’s scope. Finally, we obtained the following two blocks of search strings to collect relevant literature from prominent digital databases. These two blocks of keywords were combined with the help of Boolean operators (‘AND’ and ‘OR’) to encompass multiple facets of I4.0 and sustainability, returning results that contained keywords related to both concepts.

- **Block A** – Industry 4.0: ‘Industry 4.0’ OR ‘smart manufacturing’ OR ‘smart production’ OR ‘smart factory’ OR ‘cyber-physical systems’ OR ‘cloud manufacturing’ OR ‘Internet of Things (IoT)’ AND
- **Block B** – Sustainability: ‘sustainable business models’ OR ‘green models’ OR ‘circular economy’ OR ‘sustainable development’ OR ‘sustainable value’ OR ‘sustainable orientation’ OR ‘business model for sustainability’ OR ‘sustainability business models’ OR ‘flourishing/strong sustainable business model’ OR ‘truly sustainable business model’ OR ‘normative sustainable business model’

Our review search was based on these two blocks of keywords, although some relevant articles may have been missed; the use of specific terms in the search strings may have influenced the identification of primary papers. However, we made the terms broad and retrieved a relatively large number of papers (n = 4291). Fig. 1 outlines the literature selection process used in this study.

3. Methodology

We followed the literature mapping review guidelines described by Kitchenham et al. (2011). Mapping studies apply a methodology similar to systematic literature reviews (SLRs). However, systematic mapping studies aim to identify and classify all studies related to a broad topic, whereas typical SLRs tend to focus on questions about the qualities and applicability of different methods, technologies and concepts (Kitchenham et al., 2011; James et al., 2016). Furthermore, Kitchenham et al. (2011) state that usually, a mapping study aims to classify the relevant literature and aggregates studies with respect to the defined categories such as (authors’ names, authors’ affiliations, publication source, publication type, publication date, etc.) and/or information about their search methods used. Thus, it suits our research aim to focus on the classification and thematic analysis of literature about a given topic. Our systematic mapping review process consisted of three phases: planning, conducting and documenting.
Our search keywords targeted paper titles and abstracts with a view to retrieving as many pieces of relevant literature as possible related to I4.0 and a combination of sustainability, TBL, CE and SBMs. We retrieved a total of 4291 articles from four databases: Scopus, Web of Science, IEEE Explore and ProQuest. The search results were imported into a Microsoft Excel spreadsheet and included metadata such as article title, author, year, publication type and abstract. In phase 1, the retrieved articles were filtered based on publication date (1st Jan 2012 – 17th April 2020) and publication language (English). By the end of this process, 1233 papers were excluded and 3058 were ready for further analysis. In phase 2, we screened these 3058 articles based on title, abstract, keywords and document type (journal articles only) thus removing both conference papers and duplicates. Most of the articles were conferences papers and book chapters, which were excluded. This reduced the number of publications to 757.

These 757 papers were evaluated based on abstracts, introduction, and conclusion. The inclusion criterion was that all papers had to discuss I4.0 (either as a concept or analysed with respect to its related technologies) in relation to at least one of the SD concepts (TBL, CE, and SBMs). This means that articles using I4.0 as a keyword referring only to technological usages without having direct implications for SD were removed. In addition, articles mentioning SD only as a future research paradigm in a context out of the scope of current research, such as machine performance and accuracy, were also excluded. This iterative selection process resulted in 120 articles. In the final step, 120 papers were analysed by reading full text. These papers were assessed explicitly based on their study objectives (SD) and descriptions of their contexts (I4.0) and their relationships. This process resulted in 39 papers being excluded, as they were only marginally addressing I4.0-based SD relationship in terms of TBL, CE, and SBMs and would not have been added value to the current research. Altogether, the final selection resulted in 81 articles (see: Appendix A) which were assessed based on their properties, such as publication type and year, methods, contributions, domain, and publication channel.

![Fig. 1. Paper selection process.](image-url)
4. Results

This section presents the results from the analysis of 81 primary studies pertaining to I4.0 and sustainability. The results derived from the research questions (RQs) are presented in Table 2 below.

4.1. Publication year

This attribute was used to establish the number of articles published annually about I4.0 and sustainability between January 1, 2012 and April 17, 2020. Fig. 2 highlights an increasing publication trend, but a particularly steep increase is visible from 2018 to 2020. Of the 81 primary studies, 22 papers were published in 2018, 26 in 2019 and 14 in 2020 (up until 17th April). This growing trend in publications portrays the significance of I4.0 and its role in sustainability, particularly over the past three years. This trend suggests that scholars increasingly view SD as a vital aspect of I4.0 evolution and a key to finding solutions to industry-related problems.

4.2. Publication channel

A journal's credibility is significant in determining its public perception. This mapping review shows that Sustainability (n = 21) and Journal of Cleaner Production (n = 9) are the most prominent publication venues among those under review. Other prominent journals identified in the primary studies are the International Journal of Production Research (n = 4), Sustainable Cities and Society (n = 3), International Journal of Precision Engineering and Manufacturing-Green Technology (n = 2), IFAC-PapersOnLine (n = 2) and many others, as shown in Fig. 3. Publications in these journals outline the importance of I4.0 and its sustainability implications from a research perspective. Furthermore, the number of publications in these diverse and well-esteemed publications underscore the multidisciplinary nature of I4.0 and SD in general (Bondar, 2018).

4.3. High-contributing authors

To identify the most prolific authors, primary papers were sorted based on the first author's contribution. Table 3 highlights that Watanabe (Brazil) and García-Muiña (Spain) topped the list with 3 publications each, followed by Garrido-Hidalgo (Spain) and Müller (Germany) with 2 publications each. These authors investigated topics related to I4.0 technologies and sustainability.

4.4. Publication's country of origin

Fig. 4 shows that most of the primary studies were published by authors from Spain (n = 9), India (n = 9), Brazil (n = 8) and Italy (n = 6), whereas the United Kingdom (UK), the United States of America (USA) and Germany were represented by four publications each. It is interesting to note that articles from Germany, the flag-ship nation of digital development, are fewer than those from Spain and India written in English. This might indicate that the latter nations have become increasingly aware of how applying I4.0-related knowledge and skills can grant them competitive advantage, thereby playing a key role in their industrial survival. However, despite the rich and dynamic knowledge base about I4.0’s capabilities, its practical applications remain in their infancy within many organisations (Bondar, 2018).

4.5. Research methods used in primary studies

The primary studies were analysed to identify applied research techniques. Fig. 5 shows that a major portion of primary studies employed conceptual approaches (n = 38) followed by case studies (n = 15), surveys (n = 15), simulations (n = 6), experiments (n = 5) and mixed methods (n = 2). Mixed-method studies entail a combination of qualitative and quantitative approaches. The results predominantly show that quantitative research methods, such as experimentation and simulation, are under-represented and should be employed in further research.

4.6. Key technologies

The related research question sought to classify the core technologies that underpin I4.0. Five broad categories were identified in the I4.0—sustainability relationship, namely I4.0 concepts which encompass leading-edge technologies such as IoT, CPSs, BD, and cloud computing (CC) and theories (see Fig. 6).

The majority of the primary studies discussed general I4.0 concepts and theories in the context of sustainability (n = 32) and IoT (n = 27), used as an individual technology for addressing sustainability issues. The remaining primary studies highlight BD (n = 9), CPSs (n = 5) and CC (n = 5).

Research built on I4.0 concepts as a study environment, including mixed technologies, is the most common form of SD research. This makes sense because such studies easily highlight the theoretical and practical implications of I4.0 for educators and practitioners. Among individual technologies, IoT is the most studied SD-related technology. This is because I4.0 uses IoT to execute a wide range of digital manufacturing involving sensors and networked technologies. The connectivity offered by IoT links entire environmental networks, saves resources and minimises unnecessary expenses on water monitoring, transportation and smart grid systems. BD, the third most discussed technology following IoT, is a revolutionary information technology that can assess environmental risks and optimise resource use by analysing

| Table 2 | Research questions and their corresponding sections. |
|---------|---------------------------------------------|
| ID      | RQs                                          | Corresponding section                             |
| RQ1     | Who is working in the I4.0-based research field and where? | Descriptive results: Publication year (Section 4.1), publication channel (Section 4.2), high-contributing authors (Section 4.3) and country of origin (Section 4.4) |
| RQ2     | What key investigative research methods are being adopted in the field? | Research methods used in primary studies (Section 4.5) |
| RQ3     | Which technologies currently address SD needs in an I4.0 context? | Key technologies in the field (Section 4.6) |
| RQ4     | To what extent are key research themes in SD and 14.0 studied? | Sustainable development and I4.0 analysis (Section 4.7) |
| RQ5     | What are the interconnecting themes in I4.0-based SD research? | Themes under each sustainable development element (TBL, CE, SBMs) and I4.0 (Sections 5.1–5.4) |
| RQ6     | What are the current SD research gaps and opportunities based on I4.0? | Current research gaps under each research construct (Section 6) |
**Fig. 2.** I4.0 and sustainability-related publication trend (from January 1, 2012 until April 17, 2020).

**Fig. 3.** Publication channels of primary studies, $n \geq 2$ ($n$ represents the number of publications).

**Table 3**
Top four authors in I4.0 and sustainability research.

| Author(s) (Year) | Publication Venue | Research Themes Investigated |
|------------------|-------------------|------------------------------|
| Watanabe et al. (2018) | Journal of the Brazilian Society of Mechanical Sciences & Engineering | Social, economic, environmental, organisational and technical sustainability; I4.0; CPSs; dispersed productive systems; cloud systems |
| Watanabe et al. (2017) | IFAC-PapersOnline | |
| Watanabe et al. (2016) | IFAC-PapersOnline | |
| García-Muina et al. (2020) | Sustainability | Sustainability; CE; circular business models; industrial districts; I4.0 |
| García-Munia (2019) | Social Sciences | Social Sciences |
| García-Muina et al. (2018) | | |
| Müller and Voigt (2018) | Journal of Precision Engineering Manufacturing-Green Technology | Social, economic and environmental sustainability; IoT; I4.0 |
| Müller et al. (2018) | Sustainability | |
| Garrido-Hidalgo et al. (2020) | Waste Management | Environmental sustainability; CE; I4.0; IoT |
| Garrido-Hidalgo (2018) | IEEE Access | |
large data pools. While CPSs can connect digital and physical worlds and promote sustainable solutions by making optimal reactive and proactive decisions, and CC can consolidate large-scale cloud infrastructure to reduce negative environmental impacts,
these technologies play a comparatively lesser role than IoT in developing sustainable solutions and require further research. Overall, CPS, IoT, smart products and smart processes add to value proposition and support sustainable business.

4.7. Key sustainable development themes

As evidenced by the primary studies, SD is a multi-dimensional topic in relation to I4.0. Fig. 7 outlines the four most relevant themes in the research area on which the current study is based. A vast proportion of the primary studies address the social, economic, and environmental pillars of I4.0 technologies with a strong focus on the latter.

Alongside the TBL, CE represent a novel business mindset that can lead organisations and societies to SD (McDowell et al., 2017). Much of the identified literature applied the CE principles of the 3Rs (reduce, reuse and recycle) and 6Rs (reduce, reuse, recycle, recover, remanufacture and redesign) as I4.0 approaches. Only two primary papers discussed the ReSOLVE (regenerate, share, optimise, loop, virtualise, exchange) framework. ReSOLVE is suggested by the Ellen MacArthur Foundation, a principal global foundation developing CE plans for decision makers across the triple helix model of innovation, which includes government, business and academia (MacArthur et al., 2015). The manufacturing world is changing along with the current industrial revolution, as is sustainable value creation for businesses. Despite the significance of the subject, few papers have focused on the necessary implementation of SBMs in operational environments (Ritala et al., 2018). More research is thus required to link I4.0 practices with strategic organisational visions to foster the effective exchange of information between upper management and operational units and their interested parts. Recently, few studies have addressed more than one contributing factor of SD linked to I4.0. For example, Machado et al. (2020) studied the impact of I4.0 technologies with respect to TBL sustainability and its implications for designing SBMs. Strandhagen et al. (2017) proposed a model describing ‘how Logistics 4.0 changes the business model elements [and] the resulting sustainability effects, and in turn, [how] that sustainability affects Logistics 4.0 trends. However, more field research is required to integrate I4.0 technologies and their practical applications to the essential elements of SD.

5. Inter-related themes under sustainable development

I4.0 encompasses multiple leading-edge technologies and addresses many theoretical concepts related to the ongoing 4th industrial revolution. Its main target is innovating industry, production processes and overall SD at both the organisational and societal levels (Braccini and Margherita, 2018). Therefore, we explore and link several aspects of SD-related thinking, including TBL sustainability, CE and SBMs, that directly and indirectly support SD.

Sustainability is a multi-dimensional concept that affects the environment, the economy and society (i.e., the TBL). Economic sustainability can be obtained by improving productivity, environmental sustainability by smart energy consumption and social sustainability by creating lighter workloads and better job prospects (Braccini and Margherita, 2018). The concept of CE arose from a contemporary business mindset that seeks to help societies and organisations attain SD by restoring value to their used resources (McDowell et al., 2017; Pham et al., 2019). According to Geissdoerfer et al. (2017), sustainability also supports CE by virtue of their mutual intra- and intergenerational commitments, global models, multi-disciplinary scopes and concerns with non-economic aspects. As a practical example, García-Muina et al. (2018) proposed a new type of circular business model that integrates innovation and sustainability as strategic choices, resulting in solution-oriented business models. Machado et al. (2020) extended the debate to business value and suggested that CE based business models are optimised versions of the TBL that can be used in developing SBMs. SBMs based on I4.0 maintain a resilient, efficient, and recovery-based infrastructure, resulting in social, economic and environmental benefits contributing to long-term SD (de Man and Strandhagen, 2017).

As these subjects are dynamic, the next section provides a thematic overview of the research areas in which these themes have predominantly been studied. In doing so, a comprehensive picture of SD and its many intersecting sub-topics can be obtained. To identify themes, we followed the model by Gioia et al. (2012) to systematically analyse our primary papers in three phases. First, we identified core concepts in primary papers and labelled them as ‘first-order concepts’. We then extracted what we called ‘second-order themes’ with a focus on emerging research themes. Finally, ‘aggregate dimensions’ were found by connecting second-order themes and first-order concepts to broader research categories (see Appendix A).

5.1. I4.0 and TBL sustainability

TBL is the most studied theme under I4.0-based SD research (Fig. 7) and is thus applicable to several research areas. I4.0 is predominantly studied from the perspectives of adoption and implementation to achieve TBL benefits. Furthermore, I4.0 technologies are widely studied to help create and maintain smart

---

**Fig. 7.** Key themes under sustainable development and I4.0. I4.0-based practices leading to CE is an increasingly popular topic among researchers.
factories, smart cities and sustainable supply chains. 14.0 aims to achieve certain operational and strategic TBL benefits, such as resource efficiency, energy efficiency, renewable energy, reduced workload, competitiveness, awareness, better decision making, employee well-being and productivity. Key TBL papers and their respective applications are outlined in Appendix A.

5.1.1. 14.0 adoption and implementation for TBL

The adoption and implementation of 14.0 leading to the TBL varies based on context. For instance, Braccini and Margherita (2018) identified two possible trajectories for adopting 14.0 technologies in their empirical case study, which supported the three pillars of TBL sustainability (social, economic and environmental) with a view to achieving organisational sustainability. Beier et al. (2017) empirically compared manufacturing companies in a highly industrialised economy (Germany) and a growing industrial economy (China). Their findings suggested that digital transformation leads to environmental sustainability via resource efficiency and renewable energy, while social and technological sustainability can be achieved with intelligent assistance systems and reduced workloads. Similarly, Müller and Voigt (2018) elaborated on the concepts of ‘14.0’ and ‘Made in China (2025)’ (the Chinese version of the 14.0 concept) to assess industrial IoT-based value creation considering three dimensions of sustainability in SMEs. In terms of economic sustainability, the SMEs in a highly industrialised economy place more emphasis on operational benefits, whereas in a growing industrial economy, SMEs focus more on strategic benefits (e.g., competitiveness and individualisation). In terms of environmental sustainability, German SMEs expected high resource efficiency, whereas Chinese SMEs anticipated energy efficiency. Regarding the social aspects of sustainability, Chinese SMEs sought more refined intelligent employee assistance systems compared to German SMEs. According to Müller et al. (2018), strategic, operational, environmental and social opportunities drive the successful implementation of 14.0, whereas competitiveness and future viability are its primary challenges. Nhamo et al. (2020) used information communication and technology to measure the readiness of different countries to implement 14.0 technologies in pursuit of SD goals.

5.1.2. Sustainable smart factories

14.0-based autonomous technologies, such as IoT, have transformed traditional manufacturing companies into smart factories. While smart factories are considered sustainable, IoT is what helps these factories improve their energy efficiency and address green sustainability challenges (Wu et al., 2016). For instance, Meng et al. (2018) explored the intersection between manufacturing and sustainability, presenting sustainability in terms of energy efficiency as an important goal for smart factories. Wu et al. (2016) established a correlation between BD and green issues like environmental sustainability. They proposed two metrics, effective energy efficiency and effective resource efficiency, to meet green challenges through BD. Mahmood et al. (2020) proposed an IoT-based home automation approach to reduce energy consumption, optimise costs and encourage cleaner environments. It is also worth noting that scholars are identifying 14.0-based sustainable solutions by integrating the efforts of humans and machines to achieve customised customer-centric solutions. For instance, Casado-Mansilla et al. (2018) introduced a sensor-based architecture to keep users informed about their energy consumption. They further assessed BD-based decision making as a fruitful sustainability technique in smart manufacturing. Kumar et al. (2018) proposed a large and robust data-based layout design for manufacturing that considered all three sustainability aspects, where energy consumption maps environmental sustainability, material handling maps economic sustainability and maintenance and hazard management maps social sustainability. Furthermore, Francisco and Taylor (2019) established a novel community-based energy feedback system and offered a CPS-oriented framework to link server data to citizens; this way, people's understanding of their own energy decisions could be improved, thereby leading to greater social and environmental sustainability.

14.0 consists of a complex technological architecture (Lee et al., 2015), which makes the effective application of its technologies a frequent research topic regarding industrial performance (Dalenogare et al., 2018; Lee et al., 2015). However, 14.0 alone has a positive correlation with sustainable business performance. More specifically, Gupta et al. (2020) investigated the link between cloud-based enterprise resource planning and organisational sustainability in terms of significant performance, while Raut et al. (2019) analysed the enablers of sustainable business performance in the context of BD. Pinzone et al. (2020) introduced another perspective about fostering social sustainability via human-centric CPS; they developed a framework defining CPS-based guidelines for the well-being, learning outcomes and operational performance of workers by supporting social and operational sustainability. Corporate social responsibility has also been considered as a sustainability driver in the I4.0 context (Park et al., 2019; Scavarda et al., 2019). In addition, Gobakhloo and Fathi (2019) demonstrated that digitised manufacturing can lead to corporate survival and value creation in the 14.0 era.

5.1.3. Smart and sustainable cities

Smart cities require the sustainable application of modern 14.0 technologies to improve their inhabitants’ lives, including through increased security, healthier environments and better health care access. As few papers have built 14.0-based frameworks for smart and sustainable cities, more smart city research is required. Kang et al. (2020) designed a smart IoT-based waste collection system for households in Malaysia, whereas Piramuthu (2017) identified network-connected bicycles from an IoT perspective. Deakin and Reid (2018) also suggested that sustainable and energy-efficient low-carbon zones adopt IoT-based smart cities as a growth strategy, which could result in social and environmental benefits. Su et al. (2013) addressed environmental problems associated with urban development by proposing IoT-based environment monitoring, which can sense, process and transfer environmental information. Expanding this context from cities to countries, Baek and Park (2015) linked BD and policy issues in Korea’s SD initiatives and found that establishing computing platforms will help share data and generate environmental value. Bibri (2018) also presented a framework based on IoT-enabled BD applications to achieve environmental sustainability in future smart cities, while Moreno et al. (2014) presented an energy-efficient user-centric management system for building designs using an IoT approach.

5.1.4. Sustainable supply chains

From raw materials to end-of-life, 14.0-based technologies have changed the entire structure of supply chain management. This has, in part, changed how suppliers, manufacturers and consumers contribute to sustainable long-term solutions that benefit society, the economy and the environment alike. Luthria et al. (2020) explored the drivers of 14.0 and sustainability as they apply to supply chains and ranked ‘government supportive policies’ and ‘collaboration and transparency’ as highly significant drivers for achieving TBL sustainability in supply chains within emerging economies, such as India’s. Ramirez-Pena et al. (2020) further connected key 14.0-enabling technologies with the most significant supply chain archetypes (e.g., lean, agile, resilient and green) in the context of shipbuilding supply chains. After identifying the
shipbuilding supply chain as green and lean, they concluded that green supply chain paradigms correlate with social sustainability. They listed I4.0 technologies like additive manufacturing, cybersecurity, autonomous robots, CC and augmented reality as features that improve economic and environmental sustainability from a shipbuilding supply chain perspective (Ramirez-Peña et al., 2020). They further categorised BD, IoT and simulation as drivers of social sustainability. Furthermore, Shokouhyar et al. (2019) made direct connections between types of IoT and types of smart and sustainable supply chains, each one assessed under TBL sustainability aspects and classified as either economic, green or social IoT supply chains. These categorisations, alongside other variables, resulted in better decision making and organisational sustainability. Gruzauskas et al. (2018) identified an I4.0-based competitive strategy contributing to optimal cost management for a sustainable supply chain, thus reducing the trade-offs between environmental sustainability and cost-effective performance.

5.2. I4.0 and CE

Following TBL, CE is gaining popularity in I4.0-based SD research (Fig. 7). The research trend primarily shows a focus on advancing CE benefits through I4.0 adoption and implementation. Few studies explore I4.0-based CE benefits in sustainable supply chains, while no studies research them in smart and sustainable city or factory contexts; this topic requires further attention. I4.0-based CE approaches aim to achieve better decision making, improved cost and flexibility, eco-designs, business value, reverse logistics and product life extensions. Key CE research articles and their respective applications are defined in Appendix A.

5.2.1. I4.0 adoption and implementation for CE

Critiquing the lack of research on the relationship between I4.0 and CE to achieve sustainable operations, de Sousa Jabbour et al. (2018) proposed a roadmap for successful CE implementation through I4.0-based technologies aiming for sustainable organisations and improved decision making. They used the ReSOLVE model to assess the contributions of I4.0-based technologies to CE implementation and strategising, which was also used by Dev et al. (2020) to present a real-time decision model for sustainable reverse logistics systems. Bi et al. (2015) discussed the 6Rs (reduce, reuse, recycle, recover, redesign and remanufacture) to reconfigure industrial robots for sustainable manufacturing in SMEs. The 6Rs were used here to illustrate how industrial challenges, such as cost and flexibility, can be lightened by making robots adaptable to new tasks, increasing their utilisation rates while minimizing their costs.

Being among the pioneering researchers linking I4.0 and CE paradigms, Rajput and Singh (2019) identified 24 enablers (e.g., service, policy frameworks and artificial intelligence) and 15 barriers (e.g., automated synergies and interface modelling) to CE–I4.0 integration. To bridge the gap in empirical evidence detailing business-related aspects of CE, Rocca et al. (2020) presented a practical laboratory-based case examining the impact of I4.0 technologies on CE by testing waste from electrical and electronic equipment. They proposed that factories should adopt more service-oriented and event-driven information-based models for increased optimisation, greater efficiency and better CE support in an I4.0 era. For successful implementation, researchers have linked TBL sustainability and CE as drivers of business value. For example, Ávila-Gutiérrez et al. (2019) proposed a framework aligned with in which CE was conceptualised as a sustainability paradigm, and further linked to the TBL. This framework was then developed to address digital transformation in the CE implementation process for creating circular value. The 6Rs were also considered from a CE perspective in product life cycle design. That said, few studies have linked the effects of specific I4.0 technology implementations on CE outcomes. For instance, Ingemarsdotter et al. (2019) developed a framework to understand the practical implementation of IoT for devising circular strategies. Rosa et al. (2020) evaluated different I4.0-based technologies, such as BD analytics, CPS and additive manufacturing as CE supports, highlighting a link between I4.0 and CE. They introduced the concept of ‘Circular I4.0’ and digital CE, describing the links between them using the 6Rs. Similarly, Garcla-Muinna et al. (2019) identified eco-design as a tool to stabilise CE using IoT and I4.0. Some authors also identified specific stages of product life extension through simulation (Charnley et al., 2019).

5.2.2. Sustainable supply chains

There is limited research on I4.0-based CE models for sustainable supply chains. Yadav et al. (2020) developed a sustainable supply chain management framework to address related challenges using combined solutions stemming from I4.0 and CE paradigms. The results show that organisational and economic challenges are the most crucial ones to address in sustainable supply chain management, and the researchers proposed the 6Rs and life cycle analysis as possible solutions. Dadi et al. (2019) analysed sustainable supply chains in health care in current I4.0 environments, proposing a transition to CE through the lens of corporate social responsibility. They concluded that health care supply chains can become more sustainable by successfully integrating TBL, I4.0 and corporate social responsibility.

5.3. I4.0 and SBMs

Based on our findings (Fig. 7), I4.0-related SBM literature exists but has not yet become mainstream. Few scholars have examined I4.0 adoption and implementation for developing SBMs. Sustainable supply chains, smart cities and factories are potential areas for further research. I4.0 supports SBMs by enabling or facilitating interconnected business models, triple-layered business models, digital twin platforms, product service systems, pay-per-use models, resource integration, transparency and traceability. Key SBM papers and their respective applications are outlined below (see Appendix A).

5.3.1. I4.0 adoption and implementation for SBMs

SBMs in the I4.0 era demand sustainable practices in line with companies’ strategic visions for value creation, which creates complexity in aligning upper management’s goals with operational business units and all other Interested parts (García-Muinna et al., 2020). To address this complexity, García-Muinna et al. (2020) analysed the nature of sustainability transition and proposed corporate values leading to SBMs. They suggested a triple-layered business model unifying social, economic and environmental values via water recycling in the ceramic tile industry. Similarly, Abubakr et al. (2020) proposed that smart SBMs should be based on decentralised management, advanced technologies for positive environmental impact, transparent information, active resource and energy management and quality technical assistance. In addition, Li et al. (2020) proposed how enterprises can build SBMs using digital twin platforms to achieve TBL benefits. Another concept, cloud manufacturing, is a service-oriented business model to share manufacturing capabilities and resources on a cloud platform (Fisher et al., 2018). Cloud manufacturing increases sustainability in four keyways: (1) collaborative design; (2) greater automation; (3) improved process resilience and (4) enhanced waste reduction, re-use and recovery (Fisher et al., 2018).

Charro and Schaefer (2018) contributed to I4.0 and business model paradigms by underscoring the business implications of cloud manufacturing, offering novel ideas for product-service
systems. Their platform defined ‘use’ and ‘result’-oriented product service systems that can adapt to customers’ strategic requirements. Such systems persuade customers to trust third-party platforms to achieve manufacturing quality rather than owning physical machines. This kind of pay-per-use method motivates the social aspects of SBMs and results in decreased costs, revenue generation and competitive advantages for businesses. Watanabe et al. (2016) proposed a product system evaluation process based on CPS and CC to monitor TBL in addition to technological sustainability. Sustainable product systems were categorised to provide new business models based on rational resource/environment use that are conducive to employee safety and economic profitability, which lead to the technological and social benefits of SBMs. Regarding I4.0 in business modelling, Watanabe et al. (2017) proposed a framework based on CPS and CC technologies that can lead to cost-effectiveness, viability, safety and efficiency in sustainable product service systems. Watanabe et al. (2018) further evaluated the performance of dispersed production systems, which entail an integrative process of converting raw materials into finished products in economically, environmentally, socially, and technologically sustainable ways. They proposed a framework that includes key sustainability performance indicators. Garrido-Hidalgo et al. (2018) carried out an experiment by developing an I4.0-based technological setting that avoided social disruptions by providing safer working environments and sustainably digitalised the I4.0 paradigm.

5.3.2. Sustainable supply chains

Jeble et al. (2018) empirically analysed the impact of BD and predictive analysis on sustainable business development. They found that integrating organisational capacities and resources can create competitive advantage, further validating that BD and predictive analysis positively affect TBL outcomes when moderated by supply base complexity, which results in technological and organisational SBMs related benefits. Pause (2015) addressed the impact of I4.0 on sustainable business modelling and discussed how fractal-based information points (joining the parts around an information access point) for product life cycles in supply chains can lead to BD transparency and traceability, thereby creating social and organisational sustainability. While there is scarce literature on SBMs for sustainable supply chains, more research about business models based on environmental and social benefits is needed. They should not be considered only as the by-products for economic gains but for actual commercialization of social and environmental benefits across entire supply chains (Birkel and Müller, 2021).

5.4. Synthesis of the findings

I4.0 for SD highlights numerous opportunities within and across the individual and combined constructs of TBL, CE and SBMs (Fig. 8). It is noted that they lead to the development of resource efficiency, overall improvement of organisational structures, their skills, employee well-being and improved business value under sustainable I4.0 paradigm. While TBL align all three pillars of sustainability with respect to social, economic, and environmental objectives, CE complements by providing tools such as 3Rs and 6Rs to reach those objectives. However, both the concepts differ in terms of notion of responsibility (Geisdoerfer et al., 2017). TBL literature focuses more on achieving environmental benefits whereas CE seems closer to prioritize financial benefits (Birkel and Müller, 2021). Combining efforts to achieve TBL objectives and circularity at the same time can outline certain benefits, such as improved decision making, energy efficiency, fair distribution of costs (Gobakhloo, 2020) and eco-design. These kinds of coordinating efforts provide basis to develop sustainability-oriented business models (Ejsmont et al., 2020) based on innovation and novelty (Gobakhloo, 2020) in the ecosystem. I4.0 principle of connectivity, and CE principle of resource integration results into triple-layered interconnected business models and information-driven business models which lead to traceable and transparent product service systems that ultimately bring knowledge for value creation. This kind of innovative transformation of business models towards sustainability enables customer lifetime value, corporate profitability, competitiveness, and digital twin systems for accuracy by minimizing wastes, inefficiencies, and non-value-added activities (Gobakhloo, 2020).

Thus, to benefit from synergies of TBL, CE and SBMs, SD should be viewed as a policy-driven holistic approach that focuses on the use of I4.0 to achieve sustainable value through resource efficiency and co-optimising business and social value, which mutually benefits the environment, the economy and society. A well-planned I4.0 implementation strategy, followed by innovative policies in a diffused social and institutional environment, that includes the quintuple bottom line (social, economic, environmental, technological and organisational) and the quintuple helix (industry, government, university, environment and society) requires further consideration.

6. Future research directions

Since I4.0 transition mechanisms are diverse, systematic definitions of sustainability that encompass all elements of an integrated process are required. This challenges traditional approaches to problem solving and demands more systemic ways of addressing I4.0 transitions. Kiel et al. (2017) argued that extending beyond the traditional TBL explanation of sustainability is critical in sustainable industrial value creation. They proposed three additional TBL dimensions: technical integration, data and information, and public context. These factors imply the involvement of an integrated system comprising economic, social, environmental, technological, and organisational aspects concurrently. It is important to extend the TBL to a ‘quintuple bottom line’ by including technological and organisational sustainability, since organisations, societies, environments, and technologies are mutually dependent under I4.0. Researchers can investigate the extent to which organisations can achieve these sustainability outcomes and their ratio of significance in relation to I4.0 technologies. In addition, although much attention has been paid to TBL and I4.0 adoption, more empirical research is needed to assess outcomes like knowledge production when organisations design I4.0 adoption exclusively to achieve said outcomes (Braccini and Margherita, 2018). Similarly, antecedents to I4.0 adoption and implementation are unclear and require further attention in terms of management support, environmental uncertainty, absorptive capacity and employee acceptance levels (Müller et al., 2018).

There is an evident literature gap about I4.0-driven CE and SBMs and their contributions to smart and sustainable cities, factories and supply chains. Few papers (Maksimovic, 2018; Garrido-Hidalgo et al., 2020) have analysed the positive role of IoT-driven waste management systems in developing smart and green cities by applying the 3Rs (reduce, reuse, recycle) for waste management or smart SBMs based on decentralised management; advanced technologies for positive environmental impact, transparent information, active resource and energy management and quality technical assistance (Abubakr et al., 2020). Circularity and sustainability exhibitions create environmental benefits by reusing and recycling, which maximise material and resource efficiency and create value from waste. They can also provide energy efficiency and scale up solutions for smart and sustainable cities and factories; as such, they merit further consideration. For smart cities, CC as an I4.0
technology could have potential benefits if properly planned and standardised (Bibri and Krogstie, 2017) and then executed in line with the neglected aspects of social sustainability, such as human and community development feedback systems (Moreno et al., 2014).

In the context of smart factories, more research about I4.0-based rich data is required to evaluate reverse logistics and better control remanufacturing and product recycling (Kamble et al., 2019). Technologies such as additive manufacturing and CC for product quality management could be evaluated to advance sustainability using inline sensing and monitoring, real-time evaluation and sampling inspection (Meng et al., 2018). Furthermore, sustainable energy-efficient techniques are required for small-share energy application systems, such as bioenergy, to tackle energy use reduction and save on maintenance costs (Owdažny et al., 2018). For a sustainable supply chain, it is important to qualitatively and quantitatively explore topics like resistance to change and supply chain complexity (de Sousa Jabbour et al., 2018) using BD predictive analysis and CC by assessing their respective uses, advantages and disadvantages (Jabbour et al., 2020).

In business models, organisational capabilities and corporate social responsibilities are crucial enablers of proper SBMs and CE frameworks (Daú et al., 2019). Few primary papers have addressed TBL, CE and SBMs simultaneously under an I4.0 paradigm; instead, they have mainly focused on value creation for sustainable organisations (Ghobakhloo and Fathi, 2019; Kiel et al., 2017; Müller and Voigt, 2018). However, it is crucial to obtain quantified evidence of the relationships and interplays within I4.0 firm management, industry performance, customer preferences and sustainability at all levels (Piccarozzi et al., 2018). Combining the strategy literature with quantitative and temporal data about I4.0 adoption and implementation, its tools and issues, skillsets and capabilities, awareness of new sustainable manufacturing practices and respective decision making could create effective results in not only overall firm performance, but also industry performance. In addition, sustainability reporting on global initiatives and SD goals before and after transitions to I4.0 will serve as a checkpoint for economies moving towards SD. Rethinking business models for sustainability and CE includes a complex set of external interest holders involved in all phases of product lifecycles, which presents additional challenges and risks in the form of interdependencies. It would be interesting to study the causal relationships between socio-economic contexts (Tortorella et al., 2019), such as economic growth, income and human capital (Beier et al., 2017) and their complementary or constraining roles in developing digital technologies through empirical research (Gupta et al., 2020; Kamble et al., 2019; Rajput and Singh, 2019). Apart from the positive implications of I4.0, further research should also consider its many context-related risks, such as IT security and stakeholder interdependencies, e.g., in supply chains (Rosa et al., 2020). It should also establish sustainability-related results based on the interplay between these risks (Birkel et al., 2019).

7. Conclusion

This systematic mapping study presented current trends and state-of-the-art SD research studies in an I4.0 context. The existing SD literature was classified and reviewed through the lens of three core topics: the TBL, SBMs and CE. The primary studies showed that in an I4.0 context, SD contributes to CE objectives by developing SBMs to secure social, economic, and environmental benefits. As the TBL is the most commonly studied sustainability research theme, further attention should be given to CE and SBMs and their synergies. These inter-related themes were further categorised based on the research areas in which they have been widely studied. The purpose of this categorisation was not only to unify diverse research contributions under the common theme of SD, but also to highlight research gaps to assist concurrent fields in pursuing future research. We found that many scholars have used conceptual analysis to investigate sustainable ways to adopt and implement I4.0 technologies, mainly IoT. They have also used it to improve the discourse on economic development, social equality,
and environmental fortitude in dominant research areas, such as supply chains and smart factories. While I4.0 sustainability research has been widely conducted in the manufacturing sector, our review found little research in areas such as electronic equipment and waste (Xia et al., 2015), freight systems (Kermanshah et al., 2020), water production systems (Tomičić and Schatten, 2016), agri-food (Miranda et al., 2019), forest protection (Daj, 2016), health care (Islam et al., 2015), accounting and reporting (Tiwari and Khan, 2020) and transportation (Davidsson et al., 2016). Nevertheless, assessing I4.0 technologies using CE principles for sustainable value creation and TBL found in other sectors, such as agriculture, could elucidate many unseen dimensions for innovation and profitability.

Like other systematic reviews, our study has limitations. There are other concepts similar to CE in the literature, such as eco-efficiency (doing more with less) and lean manufacturing (waste reduction with increased efficiency), that also contribute to SD. The literature indicates that lean manufacturing, eco-efficiency, and I4.0 complement each other (Mrugalska and Wyrwicka, 2017; Varella et al., 2019; BCSD, 1993) as they seek to improve product quality, mass production, sustainable manufacturing and business performance. Since the focus of our study is broad and did not include these topics, future studies should address them. Additionally, we used a mapping study as a methodology, which established facts and answered ‘what’ and ‘how’ questions with theoretical and conceptual constructions instead of defining causes and effects. However, quantification is significant and necessary in future research, as it will help identify high-impact variables to be focused on in future I4.0—sustainability research.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.126655.

References

Abubakr, M., Abbas, A.T., Tomaz, I., Soliman, M.S., Lugman, M., Hegah, H., 2020. Sustainable and smart manufacturing: an integrated approach. Sustainability 12 (6), 2280. https://doi.org/10.3390/su12062280.

Alcayaga, A., Wiener, M., Hansen, E.G., 2019. Towards a framework of smart-circular systems: an integrative literature review. J. Clean. Prod. 221, 622–634. https://doi.org/10.1016/j.jclepro.2019.02.085.

Asiimwe, M.M., de Kock, I.H., 2019. An analysis of the extent to which I4.0 has been considered in sustainability or socio-technical transitions. S. Afr. J. Ind. Eng. 30 (6), 2280.https://doi.org/10.3390/su12062280.

Bibri, S.E., 2018. The IoT for smart sustainable cities of the future: an analytical framework for sensor-based big data applications for environmental sustainability. Sustain. Cities. Soc. 38, 230–239. https://doi.org/10.1016/j.scs.2016.11.004.

Bibri, S.E., Krogstie, J., 2017. On the social shaping dimensions of smart sustainable cities: a study in science, technology, and society. Sustain. Cities. Soc. 29, 211–220. https://doi.org/10.1016/j.scs.2016.11.004.

Boons, F., Lüdeke-Freund, F., 2013. Business models for sustainable innovation: State-of-the-art and steps towards a research agenda. J. Clean. Prod. 45, 19–30. https://doi.org/10.1016/j.jclepro.2012.07.007.

Braccini, A., Margherita, E., 2018. Exploring organizational sustainability of Industry 4.0 under the Triple Bottom Line: the case of a manufacturing company. Sustainability 10 (11), 3646–3660. https://doi.org/10.3390/su10113646.

Bressanelli, G., Adrodegari, F., Perona, M., Saccani, N., 2018. Exploring how usage-focused business models enable circular economy through digital technologies. Sustainability 10 (3), 639. https://doi.org/10.3390/su10030639.

Brown, B.J., Hanson, M.E., Liverman, D.M., Meredith, R.W., 1987. Global sustainability: toward definition. Environ. Manag. 11 (6), 713–719. https://doi.org/10.1007/BF01867238.

Brundtland, G.H., 1987. Report of the World Commission on Environment and Development: Our Common Future. Brundtland Report. UN Documents, New York.

Casado-Mansilla, D., Moschos, I., Kamara-Esteban, O., Tsalikis, A.C., Borges, C.E., Krimidis, S., Irizar-Arrieta, A., Konstantinos, K., Pijoo, A., Tzovaras, D., Lopez-Deipini, P., 2018. A human-centric and context-aware IoT framework for enhancing energy efficiency in buildings of public use. IEEE Access 6, 3414–34156.https://doi.org/10.1109/ACCESS.2018.2837141.

Charnley, F., Tiwari, D., Hutabarat, W., Moreno, M., Okorie, O., Tiwari, A., 2019. Simulation to enable a data-driven circular economy. Sustainability 11 (12), 3379. https://doi.org/10.3390/su11123379.

Charro, A., Schaefer, D., 2018. Cloud manufacturing as a new type of product-service system. Int. J. Comput. Integrated Manuf. 31 (10), 1018–1033. https://doi.org/10.1080/09537053.2016.1243728.

Daj, A., 2016. Economic and technological aspects of using IoT for sustainable environment management: the case of IoT Wildfire Detection Systems. Bulletin of the Transilvania University of Brasov. Economic Sciences. Series V 9 (2), 171–184.

Dalenogare, L.S., Benitez, G.B., Ayala, N.F., Frank, A.G., 2018. The expected contribution of Industry 4.0 technologies for industrial performance. Int. J. Prod. Econ. 203, 333–339.https://doi.org/10.1016/j.ijpe.2018.04.020.

Daú, G., Scavarda, A., Scavarda, L.F., Portugal, V.J.T., 2019. The healthcare sustainable supply chain 4.0: the circular economy transition conceptual framework with the corporate social responsibility mirror. Sustainability 11 (12), 3259. https://doi.org/10.3390/su11123259.

Davidsson, P., Hajimassab, B., Holmgren, J., Jevinger, Å., Persson, J., 2016. The fourth wave of digitalization and public transport: opportunities and challenges. Sustainability 8 (12), 1248. https://doi.org/10.3390/su8121248.

Diesendorf, M., 2000. Sustainability and sustainable development. In: Dunphy, D., O’Connor, P., O’Malley, S., O’Neill, J. (Eds.), Critical Issues in Sustainable Development. Earthscan, London, pp. 31–52.

Djelil, F., 2020. Sustainability and sustainable development: landscape approach as a practical interpretation of principles and implementation concepts. J. Landsc. Ecol. 4 (3), 5–30. https://doi.org/10.2478/jle-2020-0004.

Duk, C., Kim, J., 2020. Sustainable and sustainable development: landscape approach as a practical interpretation of principles and implementation concepts. J. Landsc. Ecol. 4 (3), 5–30. https://doi.org/10.2478/jle-2020-0004.

Duk, C., Kim, J., 2020. Sustainable and sustainable development: landscape approach as a practical interpretation of principles and implementation concepts. J. Landsc. Ecol. 4 (3), 5–30. https://doi.org/10.2478/jle-2020-0004.

Enders, S., 2017. A sustainable development roadmap for sustainable operations. Ann. Oper. Res. 269 (1), 1–17. https://doi.org/10.1007/s10479-018-2774-7.

Ekins, P., 2007. Greenhouse gas emissions from global waste management systems: a life cycle inventory approach. Resour. Conserv. Recycl. 51, 234–246.https://doi.org/10.1016/j.resconrec.2006.12.007.

Ekins, P., Simon, S., Deutsch, L., Folke, C., de Groot, R., 2003. A framework for the practical application of the concepts of critical natural capital and strong
