

Industry 4.0 technologies and sustainable warehousing: a systematic literature review and future research agenda

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Abstract

Purpose – Robust and efficient warehouse management is pivotal to the success of contemporary logistics and business productivity. Given the recent technological revolutions and the rising pressure for sustainable warehouse activities, the recent literature continues to grow on Industry 4.0 technologies and sustainable warehousing. Following this, the review aims to explore current state-of-the-art, knowledge development, the focus of research, methodological development and knowledge gaps for more impactful future research on this important yet underexplored topic.

Design/methodology/approach – A widely accepted systematic literature review (SLR) methodology was employed on a sample of 46 articles retrieved from multiple search queries in the three large databases: Scopus, Web of Science and Google Scholar.

Findings – The authors' analysis unveils several interesting findings: the positive linkage between various Industry 4.0 technologies and the three main pillars (economic, social, environmental) of sustainable warehousing; the paucity of large scale empirical research, specifically in the context of COVID-19; imbalance amid studies on three main aspects of warehouse sustainability; partial application of Industry 4.0 technologies; and disproportion in scholarly focus between numerous warehouse activities and Industry 4.0 technologies.

Practical implications – The authors integrate research findings from a pool of studies, thereby improving the understanding of practitioners on how different Industry 4.0 technologies relate to sustainable warehousing.

Originality/value – To the best of the authors' knowledge, this is the first SLR at the intersection of Industry 4.0 technologies and sustainable warehousing. Our review expands the existing knowledge base, devises a conceptual framework and suggests avenues for fruitful future research on this emerging area.

Keywords Sustainability, Industry 4.0 technologies, Warehousing, Logistics, Literature review

Paper type Literature review

1. Introduction

The term Industry 4.0, also known as the fourth industrial revolution, was first coined in Germany in 2011, referring to fully automated and interconnected technologies of the 21st century (Ali *et al.*, 2021a, b; Raji *et al.*, 2021). Some frequently acknowledged Industry 4.0 technologies include the internet of things (IoT), sensors, cloud computing, big data analytics, robotics, cyber-physical systems, artificial intelligence, among others (Stank *et al.*, 2019; Ali, 2019; Iftikhar *et al.*, 2021a, b). These technologies have tremendous potential to support economic, social and environmental aspects of sustainability (Kamble *et al.*, 2020; Dong *et al.*, 2021). Given this, an increasing interest of scholars and practitioners in the use of Industry 4.0 technologies for sustainable business operations is witnessed.

Among other business functions, contemporary logistics, which is defined as the activities of planning, realising and monitoring the efficient, effective flow and storage of goods, services and information from the point of origin to the point of consumption meeting customer needs, have been facing growing challenges in terms of sustainable practices. For instance, within the past ten years, logistics activities have been criticised for one of the main



causes of greenhouse gas emissions and environmental pollution (Ries *et al.*, 2017; Shee *et al.*, 2021). Therefore, rising pressure for sustainable operations continues to originate from public media and stakeholders, enacting various new governmental regulations (Ali *et al.*, 2021a, b; Iftikhar *et al.*, 2021a, b). Within logistics, warehouse – a planned space/building for the efficient storage and handling of goods and materials – holds a significant place and hence received great attention in recent times. Warehouse management includes the process involved in running the day-to-day operations of a warehouse. Given the fact that warehouse activities can considerably contribute to carbon footprint, today's well-informed consumers and other stakeholders increasingly demand socially and environmentally responsible warehouse operations i.e. sustainable warehousing. Sustainable warehousing is an approach of maximising the efficiency and effectiveness of warehouse operations in such a way that the firm's economic objectives can be reached, without negative impact on the surrounding environment and society (Malinowska *et al.*, 2018). Sustainable warehousing is indispensable to reduce carbon footprints, enhance a firm's brand image in public, improve international benchmarking, ensure adherence to local government policies and regulation, and most importantly, satisfy the increasing public pressure for socially and environmentally friendly business operations (Mohan Kumar *et al.*, 2017; Winkelhaus and Grosse, 2020). The success of sustainable warehousing lies in the realisation of all three pillars of sustainability: economic, environmental and social (Mostafa *et al.*, 2019; Kumar *et al.*, 2021a, b).

To effectively achieve three pillars of sustainability (economic, social and environmental) in warehouse management, in recent times, Industry 4.0 technologies have emerged as game-changing tools (Mostafa *et al.*, 2019; Ali and Govindan, 2021). In terms of economic sustainability, the fully automated Industry 4.0 technologies support economic growth (without negative impact on society and environment) of warehousing by reducing energy, water and material waste, production cost, paper consumption, errors and accidental damages (Mostafa *et al.*, 2019; Natanaree and Sriyos, 2014; Zhao *et al.*, 2019). For instance, IoT supported information sharing and visibility on order picking, loading, shipping reduces chances of errors, damages and product rejections, thereby reducing the risks of wasting the resources that are utilised in the manufacturing and distribution of a product (Ding *et al.*, 2020). Blockchain-enabled digital ledger increases transparency and traceability of warehouse operations, reducing the likelihood of product tempering, consignment rejection and economic losses. Likewise, modern robots can help move warehouse materials more efficiently with fewer chances of damage and economic losses (Ali and Aboelmaged, 2021). From a social perspective, Industry 4.0 technologies offer intelligence support systems and reduced workload for workers (Ding *et al.*, 2020). Working with sophisticated technologies also enhances the workers' safety and well-being (Mostafa *et al.*, 2019). Further, reduction in warehousing costs with efficient technologies could ultimately lead to the provision of relatively cheaper products to the community (Trab *et al.*, 2017; Mostafa *et al.*, 2019). In addition, Industry 4.0 technologies could support environmental aspects (lean and green operations) of warehouse practices. IoT systems, for instance, can control environmental conditions within warehouses through automatic sensors, which results in a remarkable drop in waste generation and accidental damages. Fully automated technologies are also considered more resource-efficient (less consumption of energy and water) (Trab *et al.*, 2017; Nantee and Sureeyatanapas, 2021). Indeed, the penetration of Industry 4.0 technologies can entirely transform the traditional business model into more sustainable warehousing.

Given the significance of Industry 4.0 technologies for sustainable warehousing, the literature at the intersection of these two concepts has been emerging gradually. While prior literature on logistics/warehouse management offers a few reviews; however, there is no evidence of a comprehensive and up-to-date review at the intersection of Industry 4.0 and sustainable warehousing. For example, Ding *et al.* (2020) offer insights on smart logistics through bibliometric analysis. Their review demonstrates the impact of IoT supported smart

logistics, challenges of IoT-based smart logistics and further research on smart logistics. Winkelhaus and Grosse (2020) offer a review of logistics 4.0, including the definition of logistics 4.0, state-of-the-art around logistics 4.0, and further research opportunities around the topic. Kumar *et al.* (2021) conducted a review of literature on warehouse transformation in the era of Industry 4.0. The review shows growth in research on warehouse automation and technological innovation and recommends further research in this direction.

As such, despite numerous contributions, there is a visible gap for the systematic literature review (SLR), mapping the research at the nexus of Industry 4.0 technologies and sustainable warehousing. An absence of information on what has already been done and what needs to be further explored may cause the scholars to ignore the significant and emerging topic of research or put forward duplicate contributions. Considering the growing literature and repertoire of benefits that Industry 4.0 technologies offer for sustainable warehouse operations, this study aims to explore the current state-of-the-art, knowledge development, the focus of research, methodological development and knowledge gaps for more impactful future research on the topic. Development of the research question (RQ) is essential to conduct a study more systematically and logically (Ali and Gölgeci, 2019). As such, our review builds upon the two main RQs:

RQ1. What are the current state-of-the-art, knowledge developments, the focus of research, and methodological development in the literature on Industry 4.0 technologies and sustainable warehousing?

RQ2. What are the fruitful avenues for future research on the topic?

This paper is structured in six sections. After the introduction in section 1, Section 2 outlines the statistics of the sampled articles. Section 4 presents the current state-of-the-art. Section 5 provides knowledge avenues for future research, while Section 6 derives conclusions and recommendations for more fruitful future research.

2. Review methodology

Consistent with our RQs, we used the SLR methodology (Tranfield *et al.*, 2003), which has been increasingly recommended to identify, collect and classify related studies in a more structured, nuanced and reproducible manner (Rhoades, 2011; Kable *et al.*, 2012). The SLR, also sometimes called a descriptive literature review, has been recognised as a better method of literature review than other forms of reviews e.g. bibliometric analysis, etc. (Wong, 2021). This is because it is the most effective method to logically explore the state-of-the-art and advance the existing scientific knowledge around a topic (Tranfield *et al.*, 2003; Wong, 2021).

For this review, a comprehensive set of keywords or a search query was generated based on reading of past literature, authors experience in the field of logistics and warehousing, and brainstorming. These keywords included *warehous** AND *sustainab** OR “economic *sustainab**” OR “environmental *sustainab**” OR *social sustainab** AND *Industry 4.0** OR “Internet of things” OR *IoT* OR “big data analytics” OR *blockchain* OR “cloud computing” OR “additive manufacturing” OR “data mining” OR “artificial intelligence” OR “artificial reality” OR “virtual reality” OR “cyber-physical system” OR “RFID” OR “Radio frequency identification” OR “real-time location system. Asterisk (*) sign was placed on the few keywords (*Sustainabl**, *Warehous*) that work as truncation or wildcard and automatically match the words or phrases that begin with word preceding * operator (sustainability, sustainable etc.).

Scopus, Google Scholar and Web of Science are among the big databases with the coverage of a wide range of articles. A combined use of these three databases ensures that an SLR is more inclusive and reliable. We have, therefore, selected three large scientific databases—Scopus, Web of Science, Google Scholar—to identify and collect the maximum

number of articles on the topic. The search query was run on 10 November 2021. Initially, we run the search query in Scopus yielding 68 articles. Inclusion and exclusion procedures should be employed to retrieve more relevant set of articles. We thus excluded irrelevant articles by reading the title, abstract and full paper. The exclusion criteria included non-English language articles; the studies that discuss warehousing operations without Industry 4.0 technologies; the articles that did not discuss sustainable warehousing + Industry 4.0; the articles with keywords in the references list only; notes and trade reports. The inclusion criteria, on the other hand, were that articles focus on Industry 4.0 technologies and sustainable warehousing.

Inclusion and exclusion criteria resulted in 32 articles from Scopus. To enhance the depth and rigour of research, we conducted the reference check of 32 articles and ran the search query (keywords) in Web of Science and Google Scholar. The articles that appeared in Web of Science and Google Scholar were matched with the Scopus dataset. By removal of duplicates, we identified 14 more articles (8 from Google Scholar and 6 from Web of Science), resulting in a total of 46 useable studies. Table 1 shows the complete search string and articles selection criteria.

Retrieval of only 46 articles does not surprise us as the topic Industry 4.0 technologies and sustainable warehousing is still in its infancy. The 46 articles were systematically reviewed, leading to several interesting findings.

3. Descriptive statistics

3.1 The trend of publications over time

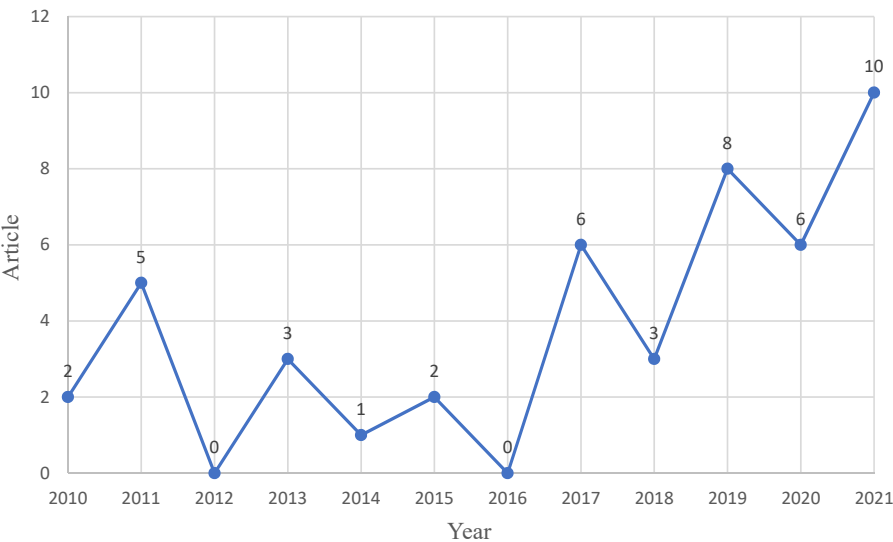
This section explains the trend of publication over time. As shown in Figure 1, while scholarly attention towards the research topic has gradually increased from 2010 to 2021, the growth pattern is quite uneven. From 2010 to 2011, there was a sharp increase in the progress of research where the number of publications in 2011 was double compared to 2010. From 2011 to 2016, there was a slowdown in the number of contributions. Surprisingly, there was no publication in 2012 and 2016.

Between 2017 and 2021, there was relatively mounting attention towards that topic, where nearly 72% of the works (33 out of 46) were undertaken within this period. Specifically, a surge in articles in 2021 can be attributed to a continuous increase in focus from scholars,

Items	Details
Keywords search query	warehous* AND sustainab* OR "economic sustainab*" OR "environmental sustainab*" OR social sustainab* AND Industry 4.0* OR "Internet of things" OR IoT OR "big data analytics" OR blockchain OR "cloud computing" OR "additive manufacturing" OR "data mining" OR "artificial intelligence" OR "artificial reality" OR "virtual reality" OR "cyber-physical system" OR "RFID" OR "Radio frequency identification" OR "real-time location system"
Databases	Scopus, Google Scholar, Web of Science
Criteria	<i>Exclusion criteria:</i> non-English language articles; the studies that discuss warehousing operations without Industry 4.0 technologies; the articles that did not discuss sustainable warehousing + Industry 4.0; the articles with keywords in the references list only; notes and trade reports <i>Inclusion criteria:</i> articles focussing on Industry 4.0 technologies and sustainable warehousing <i>Search date:</i> 10 November 2021 <i>Language:</i> English <i>Quality:</i> Peer-reviewed articles

Table 1.
Search string and
article selection criteria

Figure1.
Number of
publications per year
on Industry 4.0
technologies and
sustainable
warehousing



profit and non-profit organisations and governments towards sustainable initiatives. Following the current trend, it is projected that the research on the interconnection between Industry 4.0 technologies and sustainable warehousing will continue to receive more academic limelight in the near future.

3.2 Methodological approaches used

In terms of methodologies used by the past research, the analysis shows (Table 2) that 52.17% (24) articles were qualitative case studies, while 21.74% (10) studies included conceptual frameworks. In addition, 23.91% (11) comprised of simulation/mathematical modelling, which are mostly projection-based and without the support of real-world data. Surprising, we could find only 1 (2.18%) survey-based quantitative study. No study was found on longitudinal or action-based research approaches.

Overall, our analysis disclosed that research on the topic is still at the early stage where a major portion (73.91%) of sampled studies includes single country based qualitative case studies and conceptual framework. While qualitative studies might help add new knowledge on a novice topic, they have a generalisability problem. There is a noticeable scarcity of survey-based single as well as multimethod studies, which are considered imperative to generalise research findings through large scale studies (Ali and Golgeci, 2021).

4. Discussion on Industry 4.0 technologies and sustainable warehousing

The following section reviews the literature on the crossover of Industry 4.0 technologies and sustainable warehousing. In doing so, we have linked three major pillars (economic, social and environmental) sustainability with various Industry 4.0 technologies.

4.1 Industry 4.0 technologies and economic sustainability

Most studies in our sample (Table 2) have demonstrated that Industry 4.0 technologies can bring a wide range of economic benefits to help warehouses achieve their economic sustainability. These technologies can directly contribute to the reduction of operational

SN	Authors	Discussed technology	Sustainability aspects			Warehouse activities				Despatching	Others
			Economic	Environmental	Social	Receiving	Put-away	Storage	Order picking		
1	Wang <i>et al.</i> (2010)	RFID	X				✓	✓	✓		
2	Yuen <i>et al.</i> (2010)	VR	X		X						✓
3	Bevilacqua <i>et al.</i> (2011)	RFID	X			✓		✓		✓	✓
4	Fosso Wamba and Takeoka	RFID	X		X				✓		
5	Chatfield (2011) Lao <i>et al.</i> (2011)	RFID	X		X			✓			
6	Pacciarelli <i>et al.</i> (2011)	RFID	X		X			✓			
7	Poon <i>et al.</i> (2011)	RFID	X						✓		
8	Ballestin <i>et al.</i> (2013)	RFID	X				✓	✓			
9	Chen <i>et al.</i> (2013)	RFID	X				✓	✓	✓	✓	✓
10	Lin <i>et al.</i> (2013)	RFID	X				✓	✓	✓	✓	✓
11	Natanaree and Sriyos (2014)	RFID	X					✓	✓	✓	
12	Lam <i>et al.</i> (2015)	RFID	X		X		✓	✓		✓	✓
13	Ready <i>et al.</i> (2015)	RFID, CPS and IoT	X				✓	✓	✓	✓	✓
14	Choy <i>et al.</i> (2017)	RFID	X					✓		✓	
15	Pang and Chan (2017)	Data Mining	X					✓		✓	
16	Trab <i>et al.</i> (2017)	IoT		X							
17	Xiao <i>et al.</i> (2017)	RFID	X		X		✓	✓	✓	✓	✓

(continued)

(continued)

Table 2.
Summary of the
literature on Industry
4.0 technologies and
sustainable
warehousing

Table 2.

SN	Authors	Discussed technology	Sustainability aspects				Warehouse activities				Others
			Methodology	Economic	Environmental	Social	Receiving	Put-away	Storage	Order picking	
18	Zhou et al. (2017)	RFID	Qualitative case study	X				✓	✓	✓	
19	Zhao et al. (2017)	RFID and Cloud technology	Qualitative case study	X		X		✓	✓	✓	
20	Biswal et al. (2018)	RFID	Mathematical modelling	X					✓		
21	Lee and Choy (2018)	IoT	Qualitative case study	X		X				✓	
22	Oner et al. (2018)	RFID	Qualitative case study	X					✓		
23	Halawa et al. (2019)	RFID	Qualitative case study	X		X		✓		✓	
24	Latif and Shin (2019)	AR	case study	X						✓	
25	Leng et al. (2019)	CPS	Simulation	X				✓	✓	✓	✓
26	Liu et al. (2019a)	RFID, CPS and IoT	Qualitative case study	X			✓	✓	✓	✓	✓
27	Mostafa et al. (2019)	IoT	Qualitative case study	X	X	X	✓	✓	✓	✓	✓
28	Perisa et al. (2019)	IoT and Cloud technology	Conceptual	X		X		✓	✓	✓	✓
29	Piardi et al. (2019)	AR	Simulation	X					✓		
30	Zhao et al. (2019)	RFID	Qualitative case study	X				✓	✓		
31	Ar et al. (2020)	Blockchain	Qualitative case study	X			✓	✓	✓	✓	✓

(continued)

SN	Authors	Discussed technology	Methodology	Sustainability aspects			Warehouse activities				Order picking	Despatching	Others
				Economic	Environmental	Social	Receiving	Put-away	Storage				
32	Ding <i>et al.</i> (2020)	IoT and RFID	Conceptual	X	X	X	✓	✓	✓	✓	✓	✓	
33	Granillo-Macias (2020)	Data Mining	Qualitative case study	X					✓	✓			
34	Lorenc and Lerher (2020)	IoT and AR	Qualitative case study	X					✓	✓			
35	Zhou <i>et al.</i> (2020)	Big data technology	Simulation	X					✓	✓			
36	Rejeb <i>et al.</i> (2020)	AR	Conceptual	X		X			✓	✓			
37	Nantee and Sureeyatanapas (2021)	Industry 4.0	Qualitative case study	X	X	X		✓	✓	✓			
38	Kumar <i>et al.</i> (2021)	Industry 4.0	Qualitative case study	X	X	X		✓	✓	✓			
39	Edouard <i>et al.</i> (2021)	Industry 4.0	Conceptual	X						✓	✓		
40	Wahab and Ab Talib (2021)	AMHE	Survey based	X						✓			
41	Woschank <i>et al.</i> (2021)	Industry 4.0	Conceptual	X								✓	
42	Tyahaja <i>et al.</i> (2021)	IoT	Qualitative case study	X								✓	
43	Aamer and Sahara (2021)	IoT	Qualitative case study	X				✓	✓	✓			
44	Lin <i>et al.</i> (2021)	Cloud computing	Modelling	X					✓	✓			
45	Ruile (2021)	IoT and blockchain	Qualitative case study	X								✓	
46	Nantee and Sureeyatanapas (2021)	Industry 4.0	Qualitative case study	X	X	X		✓	✓	✓			

Industry 4.0,
sustainable
warehouse,
review

Table 2.

overheads, energy and material waste and economic losses through efficient utilisation of both human and physical resources (Fosso Wamba and Takeoka Chatfield, 2011; Lim *et al.*, 2013; Pacciarelli *et al.*, 2011; Zhou *et al.*, 2017; Edouard *et al.*, 2021). For instance, the adoption of IoT-supported RFID technology can significantly decrease operational errors, accidental damages, and resource wastage through real-time data exchange (Poon *et al.*, 2011). Ballestín *et al.* (2013) further add that this fully automated technology outplays any other technologies that involve human intervention for warehouse activities. IoT enabled RFID technology also helps to implement lean philosophy through reduction of processing time, quality deterioration and waste in warehouse operations (Chen *et al.*, 2013; Tjahaja *et al.*, 2021). Other remarkable benefits from the implementation of IoT in warehousing include increased visibility, reliability and accuracy of warehouse processes (Mostafa *et al.*, 2019; Natanaree and Sriyos, 2014; Zhao *et al.*, 2019). Reaidy *et al.* (2015) argued that the construction of IoT infrastructure is essential to increase warehouse transparency and help warehouse management improve their reactivity and competitiveness in a dynamic and complex environment. This could, in turn, boost the order fulfilment rate (Lam *et al.*, 2015; Zhou *et al.*, 2020) and reduce sub-standardised products (Lao *et al.*, 2011), leading to the firm's improved reputation and public image (Mostafa *et al.*, 2019). In their study on the economic sustainability of warehousing via Industry 4.0 technologies, Lorenc and Lerher (2020) propose an artificial reality (AR) software called "Pickup Simulo" that can provide valuable information to warehouse managers on the effectiveness and efficiency of their warehouse practices, thus mitigating the risk of resources' loss. Working on the topic of AR, Piardi *et al.* (2019) also present a simulation platform called ARENA for experimenting with advanced interactions between multi-robot systems, warehouse equipment and virtual elements within a smart warehouse. By using the simulation ecosystem of ARENA, the time, effort and related operational costs, which need to be spent on developing new warehousing strategies, can be reduced, improving the productivity of a warehouse. The economic sustainability of warehousing also receives the contribution from Industry 4.0 technologies such as cloud technology and big data analytics. For instance, Zhao *et al.* (2017) note that equipment visibility is significantly improved based on real-time data collection and communication through the cloud service, thus enhancing warehouse picking efficiency and effectiveness, as well as reducing inventory level and waste of resources on paper-based tasks. Zhou *et al.* (2020) demonstrate the powerful capability of big data analytics in improving picking efficiency and resource allocation strategy compared to traditional strategies, thereby boosting the order fulfilment rate and eventually enhancing customer satisfaction. The study of Ar *et al.* (2020) and Ruile (2021) propose the potential of IoT supported blockchain in revamping the visibility and traceability of inbound processes, which, in turn, provides better control to warehouse inventory status and inventory forecast leading to improved economic conditions. In summary, Industry 4.0 technologies play a critical role in maintaining the economic sustainability of a warehouse.

4.2 Industry 4.0 technologies and social sustainability

Literature shows some interesting studies on the societal effect of Industry 4.0 technologies in terms of warehouse operations (Table 2). For instance, new systems and models embedded in RFID technology have been introduced to offer high quality and safe products for consumers (Lao *et al.*, 2011). Lao *et al.* (2011) argue that Industry 4.0 technologies significantly reduce human errors, minimising the rate of defective goods and enhancing customer satisfaction. Mostafa *et al.* (2019) claim that IoT can help control social issues of counterfeiting, fraud or theft. Risk management is another most significant social benefit that industry 4.0 technologies can provide to warehouses staff. Lam *et al.* (2015) note that Industry 4.0 technologies contribute to risk mitigation for warehouse labour. Trab *et al.* (2017) further add

that the implementation of IoT help monitor and mitigate high-risk incidents and improve workers' safety conditions. Halawa *et al.* (2019) illustrate the capability of Industry 4.0 technologies, especially IoT supported RFID, in providing visibility to areas of safety concern. In turn, this will enhance warehouse safety standards for labour (Halawa *et al.*, 2019). Moreover, employees' work intensity can be greatly reduced through automated technology, which eventually releases pressure on workers (Pacciarelli *et al.*, 2011; Xiao *et al.*, 2017; Kumar *et al.*, 2021a, b). For example, automated systems help reduce laborious paper-based tasks (Zhao *et al.*, 2017), thereby providing a huge boost to employees' morality and work efficiency (Periša *et al.*, 2019). Altogether, it can be clearly seen that Industry 4.0 technologies provide multiple social benefits to warehouse operations.

4.3 Industry 4.0 and environmental sustainability

Despite considerable growth of research on the topic, relatively a small portion of literature appears on how Industry 4.0 technologies influence on environmental impacts of warehouse activities (Table 2). The prior studies mainly discuss how Industry 4.0 technologies contribute to the reduction of energy consumption and the carbon footprint of warehouse activities. For example, Mostafa *et al.* (2019) explicate that automatic sensors (controlled through an IoT system) help monitor the heating, ventilation and air conditioning (HVAC) system towards energy consumption. The sensor systems can capture real-time data regarding surrounding environments and then transfer it to the warehouse management systems for processing and converting it into useful information and proper actions (Mostafa *et al.*, 2019). Besides, Ding *et al.* (2020) state that the use of sensing technologies, for monitoring and managing the changes in environmental conditions, can greatly improve warehousing security and transparency. Industry 4.0 technologies can also ensure the immediate triggering of the decision-making process to decrease the preventive action time when unexpected events occur (Trab *et al.*, 2017; Nantee and Sureeyatanapas, 2021). To this end, Trab *et al.* (2017) propose an IoT connected model for real-time communication between warehouse objects to monitor, mitigate or prevent environmental disasters. In conclusion, even though with limited contribution, Industry 4.0 technologies have been found a key lever to gain the environmental sustainability of a warehouse.

5. Knowledge gaps and avenues for future research

Based on the review of literature on Industry 4.0 and sustainable warehousing, we have identified several knowledge gaps which provide opportunities for more impactful research on the topic.

5.1 Imbalance in scholars' attention on three sustainability aspects

Looking at the volume of research on each sustainability aspect, a considerable imbalance was surprisingly revealed. It appeared that the Industry 4.0 technologies for the economic sustainability of warehousing have attracted significantly greater attention of academics while the two other aspects (social and environmental) are inexplicably under-reached.

Indeed, a high volume of studies demonstrated that Industry 4.0 technologies can provide substantial economic advantages to warehouses. These advantages include enhancing warehouse efficiency (Ballestrín *et al.*, 2013); mitigating operational costs and wastage of resources (energy, material, water) (Fosso Wamba and Takeoka Chatfield, 2011; Lim *et al.*, 2013); and raising customer satisfaction level and competitive advantage (Lam *et al.*, 2015; Mostafa *et al.*, 2019; Zhou *et al.*, 2020; Nantee and Sureeyatanapas, 2021).

The social aspect is mentioned half as much as the economic. Nonetheless, the social influence of Industry 4.0 technologies holds the same importance as the economic benefits in

constructing a sustainable warehouse model. The predominantly discussed social benefits include reducing risks and strengthening worker's safety conditions (Halawa *et al.*, 2019; Lam *et al.*, 2015; Trab *et al.*, 2017; Yuen *et al.*, 2010), improving the quality and safety of products for consumers (Pacciarelli *et al.*, 2011; Xiao *et al.*, 2017), removing laborious paper-based tasks (Zhao *et al.*, 2017) and boosting employees' morality and work efficiency (Periša *et al.*, 2019).

Among the three pillars of sustainability, the researchers pay the least attention to the environmental impact of warehouse activities (Ries *et al.*, 2017; Kumar *et al.*, 2021a, b), even though Industry 4.0 technologies can help reduce a large percentage of greenhouse gas emissions (Fichtinger *et al.*, 2015). For instance, Mostafa *et al.* (2019) find Industry 4.0 technologies can reduce carbon footprints emanating from warehouse activities. Another study regarding the assistance of Industry 4.0 technologies (Evangalista *et al.*, 2017) also recognise their great potential to warehouse management in releasing pressure on green initiatives investment. The scarcity of existing research calls for more research, including the connection between Industry 4.0 technologies and the environmental aspect of warehouse operations.

In summary, while the economic aspect received greater contribution than social and environmental aspects, the number of studies, discussing all three aspects simultaneously are still scant. We, therefore, suggest a comprehensive understanding of this discipline of study to gain in-depth knowledge of all three types of benefits. This is because sustainability cannot be achieved without interconnections between all three pillars: economic, social and environmental. Our argument is in line with Strandhagen *et al.* (2017), who claim that the significant impact of Industry 4.0 technologies on the triple bottom line of sustainability should be considered as interrelated effects as they do not target a single aspect only. Further, we find the need for more empirical research to obtain more real-world evidence and innovative solutions for sustainable warehousing.

5.2 Shortage of empirical studies

Our SLR has uncovered two main methodologies used by most studies. The majorly used method is qualitative case study research to back up conceptual frameworks, see, for example, Choy *et al.* (2017), and Lorenc and Lerher (2020). The second main method included simulation/mathematical modelling, for example, Chen *et al.* (2013), Lao *et al.* (2011), Piardi *et al.* (2019), Poon *et al.* (2011), Yuen *et al.* (2010).

Qualitative case studies are popularly used as an effective tool in obtaining an in-depth understanding of a phenomenon in its real-life settings whose aspects have not yet been fully investigated (Yin, 2009). On the other hand, simulation experiments play a key role in theoretically testing the effectiveness of the proposed research initiatives.

Nevertheless, the use of simulation experiments and case studies often fail to satisfy the prerequisite for generalisability of the results, according to Dube and Pare (2003) and Yin (2009). Therefore, we suggest more survey-based and mixed methods research for the generalisability of findings. Prospective research can also use a longitudinal approach to observe the effect of Industry 4.0 on warehousing over time. We also suggest action research see transformative changes of Industry 4.0 technologies on each pillar of sustainable warehousing through the simultaneous process of doing research and taking action.

5.3 Limited application of Industry 4.0 technologies

A variety of Industry 4.0 technologies have been recently adopted in many industries given their capability to collect and analyse a large volume of data that can be used for rational decision making (Bosman *et al.*, 2019; Ali and Gölgeci, 2019). However, our SLR has recorded the partial application of Industry 4.0 technologies in warehouse sustainability.

Indeed, the use of IoT supported devices received academic spotlight, see for example Trab *et al.* (2017), Mostafa *et al.* (2019), Periša *et al.* (2019) and (Xu *et al.*, 2018). However, there is little work on other cutting-edge technologies such as big data analytics, blockchain, virtual reality and cloud technology (Arslan *et al.*, 2021). It spontaneously raises a big question mark since the practicality of those technologies in logistics and supply chains has been verified throughout the literature. For instance, Winkelhaus and Grosse (2020) conceptualise the importance of Big Data analytics in improving Logistics. In another study, Yew *et al.* (2016) state that virtual reality can enable the placement of virtualised computational objects in a real environment, which can be then used in designing products, simplifying maintenance tasks, maintaining product quality or employee training (Elia *et al.*, 2016). Blockchain can provide secure, trustful, transparent and immutable logistics operations (Ghobakhloo, 2018; Karunarathna *et al.*, 2019). Likewise, cloud technology can facilitate data pooling over the Internet or the cloud to make more informed decisions (Xu *et al.*, 2018). Cloud technology can also construct a flexible platform for collaboration and data exchange between geographically separated facilities (He and Xu, 2015).

In summary, literature has revealed a limited number of studies on various types of Industry 4.0 technology that was applied to warehouse sustainability. A comprehensive application of all key Industry 4.0 technologies is needed to achieve the full benefits of warehouse sustainability.

5.4 Imbalanced focus between warehouse activities

Industry 4.0 technologies can improve all warehouse activities, including receiving, put-away, storage, order picking, dispatching. However, our review witnesses an imbalanced focus on the impact of Industry 4.0 technologies on numerous warehouse activities. To date, most studies focus on storage and order picking while other activities are under-studied. This is questionable as the potential benefits of Industry 4.0 technologies to other activities have been recorded in the past scholarship. For example, RFID and the Internet of things can reduce the bottleneck in the traditional warehouse model where cargo receiving and despatching are heavily delayed due to unmatched goods conditions and status (Chen *et al.*, 2013). Chen *et al.* (2013) state that, with the assistance from RFID, the in/out goods flow within the warehouse can be fully controlled through digital tags embedded in the goods. Furthermore, all their associated data can be collected and shared on a real-time basis within an IoT integrated warehouse management system (Mostafa *et al.*, 2019; Chen *et al.*, 2013). Chen *et al.* (2013) believe that a significant reduction in processing time can be achieved by applying RFID. Besides, Industry 4.0 technologies can improve operations of labelling, marking, testing, packing and packaging, assembling, cross-docking, maintenance, recycling (Bank and Murphy, 2013; Lim *et al.*, 2013). Big data analytics can enormously support warehouse processes, traceability and decision-making (Periša *et al.*, 2019). Despite conceptualised benefits of Industry 4.0 technologies for various warehouse activities, there is still an imbalance in the number of studies on different warehouse activities. Therefore, we suggest more studies at the nexus of various Industry 4.0 technologies and all key warehouse activities.

6. Conclusion

Concerns for safe and healthy environment have become increasingly important over the years where sustainable solutions for warehouse management are deemed as one of the ways to reduce the carbon footprints. Sustainable warehousing can maximise resources and drive productivity whilst reducing the environment impact. To this end, Industry 4.0 technologies have emerged as a key lever to realise warehouse sustainability. The literature at the intersection of Industry 4.0 technologies and sustainable warehousing has seen growth over the past couple of years. In the light of growing literature, the objective of this SLR was to

explore current state-of-the-art, knowledge development, the focus of research, methodological development and knowledge gaps for more impactful future research. To achieve this objective, two RQs were generated. Addressing RQ1, the current state of the art was reviewed (46 articles), discussing the key findings, knowledge development, the focus of research and the methodological surrounding the topic. Doing so, our SLR implies the following: the positive linkage between various Industry 4.0 technologies and the three main pillars (economic, social, environmental) of sustainable warehousing; the paucity of large scale empirical research, specifically in the context of COVID-19; imbalance amid studies on three main aspects of warehouse sustainability; partial application of Industry 4.0 technologies; and disproportion in scholarly focus between numerous warehouse activities and Industry 4.0 technologies.

Responding to RQ2, we put forth the following research recommendations (RR) to fully explore the unveiled knowledge in this important area of study:

- (1) RR1: Our review suggests that social and environmental aspects of warehouse sustainability have received far less scholarly attention compared to economic impacts. Further research thus needs to be conducted on the impact of various Industry 4.0 technologies for all three aspects (economic, potential social and environmental) of warehouse sustainability. Given that COVID-19 has unprecedentedly disrupted various business functions and supply chains (Ali *et al.*, 2021a, b), it would be insightful if future studies explore whether and how Industry 4.0 technologies could help to resist, recover and reimagine current warehouse operations and make them more sustainable and stable operations amid COVID-19.
- (2) RR2: From a methodological point of view, we believe that currently used research methodologies cannot provide enough evidence to generalise the research results. As such, we suggest more empirical studies, including mixed-method research, multiple case study, action research and longitudinal studies to advance the methodological rigour and generalisability of findings on the topic.
- (3) RR3: As there is a limitation in the number of studies contributing to each type of Industry 4.0 technology being applied to warehouses sustainability, further research is required to obtain a comprehensive understanding of all the popularly adopted technologies and new rising ones.
- (4) RR4: In terms of warehousing activities, most of the studies focus on the two main warehouse activities – storage and order picking. Therefore, further research needs to be conducted to verify the potential implications of Industry 4.0 technologies for other warehouse activities, particularly in the wake of the COVID-19 crises.
- (5) RR5: Recent research suggests profound challenges (job-insecurity, productivity competition, antipathy, trust, etc.) related to human-machine interactions at workplace (Arslan *et al.*, 2021). As such, we suggest future research on similar issues (related to human-machine interactions) in the context of warehousing operations.

Based on the review of current literature, we devise a conceptual framework to investigate the impact of Industry 4.0 technologies on sustainable warehousing (Figure 2). The framework establishes that the influence of Industry 4.0 technologies on sustainable warehousing is mediated by economic, social and environmental sustainability. The framework can be empirically tested, thus adding theoretical contributions to the topic. While testing the proposed framework, prospective research can also use some contextual conditions (warehouse size, geographical dispersion) and other moderators, for example, internal and external integration to enhance the rigour of findings.

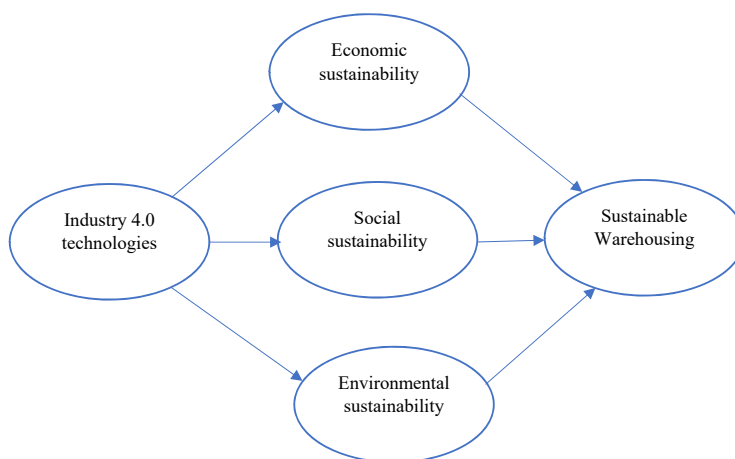


Figure 2.
Conceptual framework
at the nexus of
Industry 4.0
technologies and
sustainable
warehousing

We believe that our review will pave the way for future in-depth research to fully address the literature gaps and complete the understanding of warehousing sustainability, which has been largely underexplored. In doing so, our review would help expand the existing knowledge base and advance the field of research on an emerging topic of research – Industry 4.0 technologies and sustainable warehousing.

From the practical perspective, our review discusses research findings of different studies which may support a fundamental understanding of practitioners on how might various Industry 4.0 technologies support sustainable warehousing initiatives. This literature review can also support the underlying knowledge of policymakers and government agencies who might want to launch projects on sustainable warehousing and Industry 4.0 technologies.

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Further reading

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