Green supply chain innovation: emergence, adoption, and challenges

Abstract

Alongside many studies on greening efforts for supply chain activities, there is a research gap in understanding the emergence and adoption of green supply chain innovation (GSCI) in this digital-enabled Industry 4.0 era. This study defines GSCI as innovation practices by manufacturers that apply emergent digital technologies to integrate environmental concerns into supply chain management activities. GSCI is evolving as a new paradigm of green supply chain management (GSCM) to elevate its five underlying implementation dimensions. Manufacturing enterprises can benefit from digital technology applications to enhance efficiency of environmental outcomes of their GSCM activities, including internal environmental management, green purchasing, customer cooperation, inventory recovery, and eco-design. The GSCI concept gains growing attention in research and practice with popular digital technologies such as artificial intelligence, blockchain, cloud computing, and big data analytics increasingly adopted by manufacturers to improve their GSCM. So far, the literature lacks studies on GSCI to examine the concept, investigate the practices, explain the adoption motivations, consolidate and extend the knowledge on its adoption and diffusion. Based on a comprehensive review of GSCM literature, we explain the innovation for GSCM, and discuss the GSCI concept and practice focusing on digital technology applications with examples, and identify the challenges and opportunities for GSCI adoption and diffusion. We extend knowledge for this emerging GSCM field on digital technology applications.

Keywords: Green supply chain; Innovation; Environmental; Digital technology; Adoption

1. Introduction

The concept and practices of green supply chain management (GSCM) have been widely discussed in the last two decades due to the increasing need for pollution reduction and resources conservation. The GSCM approach requires coordinated efforts of upstream and downstream partners to satisfy the growing environmentally-conscious expectation in the supply chain (Zhu et al. 2019). In this Industry 4.0 era, there is fast development of digital technologies, where enterprises are taking advantage of emerging digital technology applications to seek green supply chain innovation (GSCI) for greater cost and service efficiencies. The Industry 4.0 development transforms business operations with enhanced efficiency, flexibility, and productivity for a higher level of sustainability by utilizing different technologies (Bai et al. 2020). Examples of these digital technologies include artificial intelligence, automation and robotics, blockchain technology, cloud/quantum computing, data analytics, 3D printing, and internet of things, which are found favourable for improving the supply chain performance of enterprises and industry development (Fatorachian and Kazemi 2021). GSCI is a further step beyond GSCM by deploying digital technologies on its different implementation dimensions to transform enterprises' supply chain activities for performance improvements with an environmental focus. For environmental supply chain collaboration, such innovation can enhance process integration among partner firms and promote ecological modernization of their operations (Zhu et al. 2012b). Increasing digital technology applications reflect GSCI as a new paradigm, which is evolving to improve GSCM implementation and performance outcomes at the next level.

Recently, there is growing attention for GSCI in both research and practice. For instance, the role of quick response technology in contribution to better GSCM was investigated (Li et al. 2019a). The concept of green supply chain collaborative innovation and linkages with absorptive capacity of enterprises and innovation performance were empirically examined (Hong et al. 2019). There are also studies investigating how specific investments can influence GSCI performance as well as the role of knowledge transfer and supply chain partner responsibility (Wu and Li 2020).

Indeed, employing innovation for GSCM as a legitimate action to meet market expectations for sustainability requirements is favourable for firms to improve their market value (Feng et al. 2020). There are growing regulatory requirements mandating environmental protection around the globe, urging the development of green products and process innovation for compliance and performance improvements (Qiu et al. 2020). These green product and process innovations are an important part of supply chain activities to improve their GSCM performance further. As digital technologies become increasingly popular among enterprises for enhanced performance outcomes, a systematic study examining the GSCI concept and practice is helpful to increase awareness of related innovation practices for GSCM.

This study is one of the first to examine the concept and practices of GSCI, despite that many studies have examined this topic indirectly by linking Industry 4.0 and GSCM (Liu and De Giovanni 2019; Umar et al. 2021). A systematic analysis is still lacking on the types of adopted digital technologies, the performance value, the adoption motivation, and the challenges evolving from GSCM to GSCI. This study examines the GSCI concept and practice as a new paradigm of GSCM evolution that focuses on digital technology applications to enhance its five implementation dimensions (see Table 1). In particular, the GSCI concept and practice are explained using examples together with the literature review on ten specific digital technology applications (see Table 2) in GSCM implementation dimensions from the perspectives of pollution control, energy efficiency, resources efficiency, and others.

To promote supply chain-wide adoption of GSCI, it is crucial that the focal firms and their supply chain partners have a consensual understanding of the concept and adopt the practices to couple with the GSCM activities. To diffuse GSCI in the supply chain, the "what" and "why" issues regarding GSCI adoption shall be clear to the adopters by providing evidences of actual practices and the performance value. Despite the past research efforts examining GSCM evolution, there are still many unanswered questions on the innovation for GSCM in this digital age and the challenges about the future of GSCM in terms of GSCI. The following research questions guide this work to advance knowledge of GSCI.

RQ1: What is the innovation for GSCM in the digital era? How can digital technologies improve GSCM?

RQ2: What have been done about GSCI in research?

RQ3: Why are GSCI practices adopted?

RQ4: What are the challenges and opportunities for GSCI?

Guided by the above research questions, this study makes several important academic and practical contributions. First, we extend the knowledge on GSCM research to examine the innovation aspects as well as the concept of GSCI with a focus on digital technology. It provides the first literature review of GSCI on its development, where the GSCM literature has seen remarkable growth, particularly in 2010-2021. Second, we explain the adoption motivations for GSCI with theoretical discussion. Third, we identify the challenges and opportunities to adopt and diffuse GSCI with suggestions for managers to plan improvement actions for GSCM in the digital era.

The rest of this study is organized as follows. Section 2 discusses the development and types of innovation for GSCM, and the evolving GSCM innovation with digital technologies as GSCI. Section 3 presents a literature review to identify the conceptual elements and characteristics of GSCI in published studies and a classification of ten digital technologies applied in five GSCM implementation dimensions to achieve three GSCM objectives on pollution control, energy efficiency, and resources efficiency. Section 4 explains the adoption motivation for GSCI with the management theory perspectives on cost-efficiency, diffusion of innovation, institutional, resource-based, and resource-dependence to provide managerial insights on what, why (or why not) and how (or how much) GSCI practices are adopted (or not adopted). Section 5 discusses the challenges and opportunities for GSCI adoption. Conclusions of this study with future research directions are provided in Section 6.

2. GSCM and innovation

2.1 GSCM development

While supply chain management is widely practiced by many manufacturing enterprises to improve their operational efficiency, there are both regulatory and market pressures for pollution control and waste to preserve the environment in the product movement processes (Sarkis et al. 2011). GSCM gradually becomes an ecological modernization tool for enterprises to balance the environment with productivity gains (Zhu et al. 2011). In the last two decades, GSCM has been widely discussed in research and adopted in practice. We have witnessed growing studies examining GSCM practices and performance with the sharp increase of related publications appearing after 2010 (Tseng et al. 2019a). Meanwhile, enterprises have been integrating green elements into their supply chain operations due to pressures from various stakeholders, including market customers, policy makers, government officials and non-government organizations of environmental concerns, and competitive rivals to conserve resources and reduce pollution for environmental sustainability (Zhu and Sarkis 2007). There are policy actions and targets for carbon neutrality in both developed and developing countries to mandate enterprises for greening their supply chain activities, such as enacting the extended producer responsibility regulations. These policy requirements promote regulatory policy awareness of enterprises, which in turn accelerates environmental supply chain cooperation and diffusion of GSCM in different industrial sectors (Mondal and Giri 2021). These developments highlight the importance of GSCM for enterprises to ease the environmental degradation caused by their activities in the supply chain. GSCM continues to diffuse in different industrial sectors because of its value for enterprises to fulfill environmental regulatory requirements, promote the corporate environmental image, meet the public expectation for environmental preservation, and improve productivity in their supply chain operations (Zhu et al. 2018).

GSCM involves the integration of environmental concerns into supply chain operations, covering five implementation dimensions (Zhu and Sarkis 2004). These dimensions include 1) international environmental management (IEM); 2) green purchasing (GP); 3) customer cooperation with environmental concern (CC); 4) investment recovery and logistics (IR); 5) eco-design (ECO). There are also different types of green practices adopted by enterprises to improve their supply chain operations. In a study of green practices in GSCM, 21 green practices are identified and classified into four groups regarding whether they are collaborative, innovative, related to operations, or mitigating, and their performance value is verified with case evidences (Sellitto et al. 2019).

GSCM is fast evolving in the Industry 4.0 era, yet the role of innovation in GSCM lacks related studies. For environmental innovation activities to take place, they usually come with novel ideas in processes, policies, and technologies (Rennings 2000). Studies have also employed GSCM as a process innovation to improve supply chain activities on the environmental side (Cousins et al. 2019). Due to the awareness of environmental policies such as the extended producer responsibility and the WEEE laws, GSCM is adopted to integrate compliance with these regulatory requirements into supply chain operations for compliance (Zhu et al. 2018). Broadly speaking, there exists two types of management innovation, i.e., technological and non-technological innovation (Damanpour and Aravind 2012). GSCM is also covered in these two types of management innovation. The former type of technological innovation is novel for GSCM with many emerging digital technologies recently adopted in practice, but there is a lack of studies to consolidate the knowledge. The latter type of non-technological innovation, including internal and external supply chain cooperation (Zhu et al. 2013; Cousins et al. 2019), environmental management capabilities (Wong et al. 2012; Inman and Green 2018; Tseng et al. 2021), and sustainability orientation (Shou et al. 2019; Guo et al. 2020), are inherent features of GSCM with documented evidences. The following parts will further discuss the innovation for GSCM and examine the application of digital technologies in the five GSCM implementation dimensions with examples.

2.2 Innovation for GSCM

Innovation is important for enterprises to improve their processes, including those for GSCM to bring both cost and service performance. Researcher have discussed supply chain innovation to cover areas in logistics, marketing, and technological development activities (Wong and Ngai 2019). There are also studies investigating the link between green innovation and firm performance with empirical evidences (Zhang et al. 2019). These green innovation activities mainly cover adoption of green technology, improvement of energy efficiency, and reduction of carbon emission (Zhang et al. 2017; Chai et al. 2018; Sun et al. 2019). The classification of these innovation activities along the five GSCM implementation dimensions can be categorized into two types, i.e., traditional research and development (R&D)-based technology and emerging digital technology. For the latter type, they facilitate informed decision-making and improve productivity for GSCM among involved parties. Related technology applications include artificial intelligence for automated GSCM operations such as analyses for environmental regulation compliance, blockchain technology for product tracking to facilitate investment recovery in GSCM among partner firms, cloud computing to support supplier benchmarking for product acquisition and timely communication in green purchasing as well as big data and analytics to enable eco-design in GSCM.

2.3. Digital technology applications for GSCM

Digital technologies play critical roles in bringing GSCM activities associated with the next higher performance level. Under Industry 4.0, digital technologies transformation supports manufacturing activities and systems in three components: hardware, software, and connectivity (UNIDO 2019). According to UNIDO (2019), digital technologies in the era of Industry 4.0 include hardware, software, and connectivity, which advance manufacturing activities and integration in operations between supply chain members. Hardware includes tools (i.e., 3D printers), tooling and the equipment of industrial robots cooperating with workers (collaborative robots (cobots)), as well as intelligent automated systems. Software includes data/information processing & communication technologies (artificial intelligence (AI), big data, cloud computing, machine learning (ML), blockchain), cyber-physical systems (CPS) with data analysis. Connectivity is achieved through embedded sensors, processors, and actuators in hardware to sense and interact the physical products and processes through software data analytics. Internet of thing (IoT) and digital twin are examples of digital technologies enabling connectivity. Based on the grouping of digital technologies by UNIDO (2019), we identified ten digital technologies useful for improving GSCM to examine the GSCI concept in this study. Their definitions and explanations are seen in Appendix.

Technological advancements support GSCM activities and offer tremendous potential and advantages, including better information traceability and management, enhanced communication and cooperation across the entire supply chain, and improved reliability and trust among the supply chain parties. Emerging digital technologies and their promising advancements for GSCM are considered as GSCI, which refers to innovation practices associated with emergent digital technologies for enterprises to integrate environmental concerns into supply chain management activities. GSCI supports green initiatives at various supply chain levels – internal environmental management (IEM), green purchasing (GP), cooperation with a customer (CC), investment recovery (IR), and eco-design (ECO). While certain digital technologies for GSCI may be integrated with each other to provide greater synergistic benefits, stand-alone adoptions are also common. Table 1 describes the five GSCM activities and provides examples of their advanced GSCI practices by digital technologies.

Table 1. GSCM implementation dimensions and digital technology applications

	Descriptions	**Digital technology applications for GSCM practices**
Internal environment management	Organizational environmental management activities that aim to improve internal firms' environmental performance, i.e., the use of green facilities and resources as well as the decisions to invest in green technologies.	Use of IoT to monitor energy consumption and improve the system automation.
Green purchasing	Environmental management practices related to suppliers, materials, and purchasing processes.	Blockchain adoption in tracing environment information of materials.

Customer cooperation	Involvement of customers through collaboration, promotion, etc. to promote products' greenness in usage stage.	Big data technology in analyzing consumers' behaviors in product use and intelligent promotion of environmental behaviors.
Inventory recovery	Recovery of resources including end-of-life products, idle equipment/material, etc.	Blockchain to track the products' life cycle data for making decision on recovery policies, i.e., reuse, recovery, or remanufacturing.
Eco-design	Product or process design for the environment	Use of machine learning and big data to simulate consumer behaviors for sustainable product design.

So far, there is a lack of systematic studies examining the concept and practice of GSCI in manufacturing operations that focus digital technology applications for GSCM implementation. To fill this literature gap, this study defines GSCI as innovation practices by manufacturers that apply emergent digital technologies to integrate environmental concerns into supply chain management activities. In the next step, we provide a review of the literature covering GSCI practices with digital technology applications in enabling GSCM implementation to achieve the GSCM goals of pollution control, energy efficiency, and resources efficiency. As GSCI becomes more established in both research and practice, it is desirable to gain a deeper understanding of its adoption and diffusion and advance knowledge in the field. We also discuss GSCI adoption with relevant organizational theories and identify challenges for GSCI development to extend the knowledge frontier. In sum, the contributions of this study are summarized below:

- Examine the innovation for GSCM and the development in GSCI;
- Define the concept of GSCI and identify the GSCI practices based on literature evidences;
- Provide insights on GSCI adoption with explanations using organizational theories;
- Identify challenges and opportunities for GSCI research and practice.

3. GSCI practices

Emergent digital technologies play critical roles in leveraging GSCM activities (Sarkis et al. 2021; Bai et al. 2020). GSCM inherently includes activities that integrate or cooperate with upstream suppliers, downstream customers, and reverse supply chain environmental management practices (Zhu and Sarkis 2004). Scholars have observed that digital technologies support GSCM activities by providing better information traceability, enhancing communication across the entire supply chain (Baumers et al. 2013; Liang et al. 2018; Liu et al. 2019; Guo et al. 2020). Digital technologies can be enablers for GSCM (Sarkis et al. 2021; Silva et al. 2019). In this section, we conducted a systematic literature review to identify the conceptual elements and characteristics of GSCI in published studies. The review advances knowledge of GSCI characteristics in its five GSCM implementation dimensions enabled by the ten digital technologies listed in Table 1. We used a combination of GSCM practices-related terms and digital technologies-related terms to carry out search in the database of *Web of Science* from 1985 to 2021. The searching is restricted in title, abstract, keywords, and only peer-review journal articles are retained for analyses (excluding non-English papers, book chapters, conceptual work, conference papers). The searching process and filtering results are shown in Figure 1. The keywords searching for digital technologies are: *3D printing (additive manufacturing), Artificial intelligence, Big data, Blockchain, Cloud computing, Collaborative robot (cobot), Cyber-physical system, Internet of Things, Machine learning, Digital twin.*

These digital technologies have been mainly applied in diversified fields. These fields were included to increase the reliability for the literature search. We invited two consultants from industries to participate in this study. To ensure the relevancy and sufficient coverage of our search terms, they were requested to list the typical application fields of the above digital technologies. Based on their suggestions, we also included the following keywords that are usually applied in specific fields: *Industry 4.0, Intelligent/Smart manufacturing, industrial IoT (IIoT), Intelligent logistics, digital marketing, network collaborative manufacturing, Smart manufacturing, smart factory, smart sensor, 5G*. Six groups of keywords searching for GSCM are used to represent general GSCM and its five implementation dimensions, which were identified based on the extant works in the GSCM field (Zhu et al. 2005; Zhu et al. 2012a; Sarkis et al. 2011): IEM, GP, CC, ECO, and IR. We list all keywords used to represent GSCM in Figure 1 as follows.

a) General GSCM: (*"Green supply chain" OR "environment* supply chain" OR "sustainab* supply chain"*)

b) IEM: (*"Green manufact*" OR "environment* manufactur*" OR "sustainab* manufactur*" OR "Green factor*" OR "environment* factory" OR "sustainab* factory" OR "Green operation" OR "environment* operation" OR "sustainab* operation" OR "internal environment management" OR "Eco-label*" OR "green standard*" OR "environment* standard*" OR "environment* management system*" OR "ISO 14001" OR "green certificate*" OR "environment* certificate*"*)

c) GP: (*"Green purchas*" OR "environment* purchas*" OR "sustainab* purchas*" OR "Green procur*" OR "environment* procur*" OR "sustainab* procur*" OR "Green sourcing" OR "environment* sourcing" OR "sustainab* sourcing" OR "Green suppl*" OR "environment* suppl*" OR "sustainab* suppl*" OR "Green material*" OR "environment* material*" OR "sustainab* material*" OR "Green component*" OR "environment* component*" OR "sustainab* component*"*)

d) CC: (*"Customer* cooperat*" OR "cooperat* with customer*" OR "Green market*" OR "environment* market*" OR "sustainab* market*" OR "Green promot*" OR "environment* promot*" OR "sustainab* promot*"*)

e) ECO: (*"Green design" OR "environment* design" OR "sustainab* design" OR "design for environment" OR "design for the environment" OR "design for sustainab*" OR "environment* friendly design" OR "sustainab* friendly design" OR "Eco-design"*)

f) IR: (*"Investment recover*" OR "reverse logistics" OR "close* loop suppl*" OR "reverse supply chain" OR "recycl*" OR "remanufacture*" OR "end-of-life"*)

The combination of the keywords from digital technologies and GSCM was finally used in the literature searching process, i.e., ("digital" keywords AND "IEM" keywords). Initially, 369 publications were identified. After removing duplicates, we kept 364 papers for the next filtering. We further screened out papers that are not related to both GSCM and digital technologies based on their titles, abstracts, and the full texts. Then, 197 papers were kept. Last, we read the full text of each paper to ensure the main research framework having relevancy to the management field rather than technologies or other fields, and this process retained 161 papers for our further analysis.

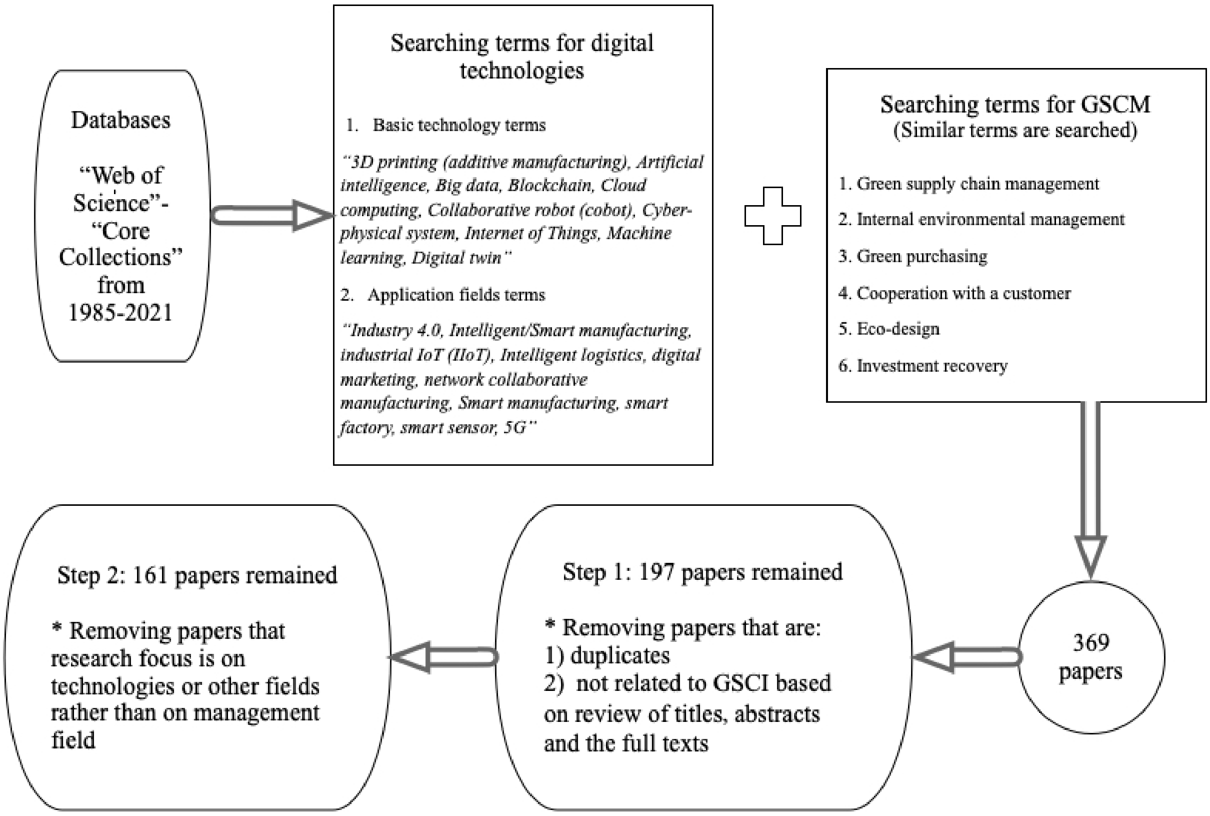

Figure 1. Literature searching and filtering process

Totally 161 papers were searched and adopted for further analyses. According to the definition of GSCI, we read the extant papers and coded them based on digital technologies applied in certain GSCM (GSCI) practices first. For example, Guha and Kumar (2018) discussed the potential of using cloud computing in IEM practice of smart and sustainable manufacturing, and thus we coded this paper in the category of cloud computing enabled GSCI (IEM). To observe potential outcomes of GSCI practices adoption, we further categorized papers based on their reporting performance indicators from a sustainability perspective: pollution control targeted (e.g., wastes, carbon emission, in Section 3.1), energy efficiency targeted (e.g., renewable energy, energy efficiency, in Section 3.2), and resource efficiency targeted (e.g., lower materials consumption, operations efficiency improvement, in Section 3.3). For example, we coded Esmaeilian et al. (2020) as "energy efficiency targeted GSCI practices" because it discussed the adoption of AI to promote customers' energy conservation behaviors (CC). As highlighted in the subsections below, digital technologies empower GSCM with their various applications for improving at least one of these three GSCM objectives. The distribution of 63 papers from three objective-oriented perspectives is shown in Table 2, which lists the digital technologies for GSCI practices, their intended objectives, and representative studies.

3.1 Pollution-control targeted GSCI practices

Pollution reduction is a major goal of GSCM activities (Liu et al. 2018). Compared to energy management and resource efficiency, pollution control is often externally driven by stakeholders such as the government, the public, or the consumers (Liu et al. 2018), and is relatively easier for firms to achieve through traditional GSCM activities, i.e., investment in cleaner equipment/technology. Studies on GSCI concerning digital technology applications in GSCM generally lack focus on pollution-control, compared to those of energy management and resource efficiency.

GSCI practices for pollution reduction mainly utilize digital technology of AI, big data, ML, and blockchain. For instance, Esmaeilian et al. (2020) analyzed the mechanism of incentivizing green behavior through blockchain recorded tokenization to motivate consumers in environment-friendly behaviors such as generating less wastes or choosing green commuting ways. For IR, AI can be used in remanufacturing activities to calculate real-time end-of-life product data to process remanufacturing parameters for pollution reduction by generating less wastes (Kerin and Pham 2019). Furthermore, big data technology is useful for emission accounting in reverse logistics activities as IR for pollution reduction (Yin et al. 2021). Big data technology is also useful for GP in detecting suppliers' environmental violation behaviors (Chang et al. 2021) and for IEM supported by ML in sustainability facility layout optimization to reduce CO2 emission (Tayal et al. 2020). There are evidences of multi-national manufacturers such as Apple and Hewlett-Packard using big data analytics to monitor their direct and some indirect suppliers located in China concerning their environmental pollution violation behaviors (IPE 2021).

3.2 Energy-efficiency targeted GSCI practices

Energy efficiency is another target improvement area of GSCI. Manufacturers use digital technology applications or replace with clean technology to improve their energy efficiency due to the pressures for internal stakeholders such as cost saving for stockholders (Liu et al. 2018).

For IEM, innovative practice such as 3D printing is recommended by researchers such as Gebler et al. (2014) to replace the original manufacturing process due to its greater advantage in reducing energy consumption. There are also advantages of using AI for GSCM activities in IEM (i.e., monitoring energy consumption (Baumers et al. 2013)), CC (i.e., using AI equipment to promote consumers' conservation behaviours (Esmaeilian et al. 2020)), ECO (i.e., design of a smart and green product system (Bai et al. 2020)), and IR (remanufacturing to save energy). Moreover, data analytics tools are enablers for green product deployment to save energy in ECO (Bag et al. 2020). Big data-based evaluation of energy efficiency analysis in production facility design also receives research attention such as (Tayal et al. 2020). Cloud computing is useful for assessment of products' carbon footprint throughout the life cycle to improve energy efficiency of ECO (Xing et al. 2016). Cyber-physical system (CPS) is helpful for improving energy efficiency in IEM related activities such as automatedly matching online systems and production equipment (Liang et al. 2018; Li et al. 2019b; Ma et al. 2019; Park et al. 2020). Digital twin can benefit ECO for less energy consumption through intelligent detection robotics (He et al. 2021) as well as through design of reduced energy consumption in cold chain logistics (Defraeye et al. 2019). Due to its data traceability, blockchain technology is useful for ECO in life cycle analysis for sustainability (Zhang et al. 2020), transparent supply chain (Baumers et al. 2013; Hastig and Sodhi 2020), green energy certification adoption in supply chains (Zhao et al. 2020). In practice, a CPS system could be used to improve the energy efficiency of the dyeing process for small factories, which contributed approximately 10.69% of energy efficiency (Park et al. 2020).

3.3 Resource efficiency targeted GSCI practices

There are external (i.e., the society) and internal (i.e., the firm) stakeholder forces driving resource efficiency. It is more difficult to achieve resource efficiency than those of pollution reduction and energy conservation in traditional GSCM activities without a common tool to manage the behaviours of multi-players (Liu et al. 2018). Digital technologies improve traceability and integrated data flows enabling inside and outside stakeholders to collaborate for resource efficiency.

With 3D printing, resource efficiency is enhanced with lower materials requirements and wastes in the printing process (Baumers and Holweg 2019; Ghobadian et al. 2020; He and Bai 2021) and more repeated use of materials (Baumers and Holweg 2019). Manufacturers such as General Electric Co. adopt 3D printing technology to simulate its production line of airplane engines before formal production, in such a way to save time and resources on product testing (Eletric 2017). AI supports IEM activities such as enabling workforce skill improvement in automation (Bag et al. 2021), optimal production planning (Fang et al. 2016), and automated product disassembly (Liu et al. 2019). AI also improves ECO with predicted data of product life cycle (Bai et al. 2020) and IR in intelligent defect detection (Guha and Kumar 2018; Kerin and Pham 2019).

Big data technology is helpful for CC to improve maintenance schedule and accuracy of predicting products' remaining life (Kumar et al. 2018) and for IR in warranty and maintenance to maximize product life cycles (Alqahtani et al. 2019) and to increase the accuracy of reduction, reuse, and recycle analyses (Bag et al. 2021). In addition, cloud computing benefits IR in activities such as inventory management for efficiency (Guha and Kumar 2018). Collaborative robot (cobot) helps manual processing manufacturing (crafting) (Guha and Kumar 2018) and manufacturing system processing speed and efficiency (Wang 2015). IoT enables IEM in smart/intelligent and green/sustainable manufacturing (Alberti et al. 2019) and IR practice. Example applications of IoT for IR to improve resource recovery efficiency include improving efficiency in use and extending lifetime through IoT-enabled tracking, monitoring, and optimization capabilities (Charnley et al. 2019; Ingemarsdotter et al. 2019; Garrido-Hidalgo et al. 2020), warranty and maintenance analysis of sensor embedded products (Alqahtani et al. 2019), recovering system of returned products (Fang et al. 2016), end-of-life product monitoring system (Garrido-Hidalgo et al. 2019), collection of used products (Ketzenberg and Metters 2020), quality management in product recovery (Ondemir and Gupta 2014), smart logistics (Tran-Dang et al. 2020a, 2020b), smart circular product-service-system (Alcayaga et al. 2019). Moreover, resource efficiency can benefit from blockchain technology applications. Examples cover ECO in improving visibility across the entire product lifecycle (Esmaeilian et al. 2020), IEM in collaborative warehouse management (Esmaeilian et al. 2020), IR in waste management traceability (Gopalakrishnan et al. 2021), GP in resources sharing with suppliers (Sarkis et al. 2021), and CC in consumer information capture (Wang et al. 2021).

There are also research works on GSCM practices through collaboration or network design to achieve all the above three objectives on pollution control, energy efficiency, and resource efficiency through deploying digital technologies (Guha and Kumar 2018; Singh and El-Kassar 2019; Tseng et al. 2019b; Wang et al. 2020)

4. GSCI adoption theories

While GSCI are gaining popularity for greener supply chain operations, managers need to justify their adoption. The decision of firms on whether to adopt a GSCI and the underlying rationale is an important management inquiry regarding the innovation adoption. There are several theoretical lens useful for explaining innovation adoption on such decision issues as 1) what are the operational benefits of adopting GSCI; 2) whether innovation adoption varies among supply chain parties and what are the innovation characteristics to learn from; 3) why one firm chooses to adopt a GSCI while another resists/ follows in the supply chain; 4) what are the incentives to motivate GSCI adoption in the supply chain; and 5) whether and how the institutional context influences the adoption decision. While many other management theories can explain GSCM adoption, the following five theories, in alphabetical order, are suggested for integration into further GSCI research.

4.1 Cost-efficiency perspective

For new practices or technologies, it is natural for firms to weigh the costs incurred relative to the benefits (efficiency) generated from the adoption. This concept of cost-benefit analysis is fundamental for firms to determine whether innovation such as GSCI should be employed to improve their operations. From the cost-efficiency perspective, digitalization improves efficiency of GSCM but also has rebound effect possibilities, where efficiency usually brings less expensive materials/components per unit usage and thus can motivate greater use overall (Sarkis, 2019). Digital technologies adoption must consider the operating and adoption cost, increased energy cost, and technological immaturity. However, GSCM concept and practice have been developed for more than two decades where related management tools and technology investment are mature and well-recognized by firms. Thus, the trade-off dilemma between cost and efficiency is less a concern for GSCM than for GSCI. The cost-efficiency of innovation such as GSCI should allow a firm to execute its operations at the same or even greater performance level using less resources inputs. It requires proper planning, control, and monitoring of their invested innovation in order to achieve the targeted efficiency. This cost-efficiency perspective is crucial in determining the adoption of GSCI in their operations, particularly those small-sized enterprises in the supply chain due to their lack of financial slacks. They tend to be more hesitant to invest in GSCI without demonstrated cost-efficiency benefits. Indeed, there are opportunities and challenges for improving cost-efficiency through adopting GSCI. To coordinate upstream suppliers for green purchasing and eco-design for products, an enterprise needs to conduct numerous planning and execution activities where the deployment of digital technologies such as cloud computing can expedite the process and save costs in communication and information exchange. Nevertheless, the cost-efficiency evaluation for GSCI adoption can be unclear for short-term benefits due to other cost elements such as staff training and process-redesign and for long-term value in view of the fast-evolving technological development and market changes.

Table 2. GSCI practices in literature

	Pollution control	**Energy efficiency**	**Resource efficiency**	**Others**
3D printing (additive manufacturing)	*N.A.*	IEM Less energy is required in the printing process (Gebler et al. 2014)	IEM Materials waste is lessened (Ghobadian et al. 2020) GP Less materials are required (Baumers and Holweg 2019; He and Bai 2021) IR High deficit prediction capability (Baumers and Holweg 2019)	*N.A.*
Artificial intelligence	IR Remanufacturing (Kerin and Pham 2019)	IEM Energy consumption monitoring (Baumers et al. 2013) CC Energy conservation behavior promotion (Esmaeilian et al. 2020) ECO Smart product design system (Bai et al. 2020) IR Remanufacturing (Kerin and Pham 2019)	IEM Workforce skills improvement (Bag et al. 2021) Optimal production (Fang et al. 2016) Product disassembly (Liu et al. 2019) ECO Smart product design system (Bai et al. 2020) IR Defect detection (Guha and Kumar 2018) Remanufacturing (Kerin and Pham 2019) GP Supplier selection (Bai et al. 2020)	*N.A.*
Big data	GP Suppliers' environmental violation detection (Chang et al. 2021) IEM Sustainable facility layout design to reduce CO2 emission (Tayal et al. 2020) IR Emission accounting in shipping activities (Yin et al. 2021)	ECO Enabling green product deployment (Bag et al. 2020) IEM Sustainable facility layout design to elevate energy efficiency (Tayal et al. 2020)	CC Optimize maintenance schedule and improve accuracy of predicting products' remaining life (Kumar et al. 2018) IR Warranty and maintenance analysis (Alqahtani et al. 2019) Reduce, reuse, and recycle capability (Bag et al. 2021)	Green supply chain collaboration and green digital learning orientation (Benzidia et al. 2021); Big data improve sustainable performance (Singh and El-Kassar 2019; Tseng et al. 2019b; Wang et al. 2020); General supply chain design (Guha and Kumar 2018);
Cloud computing	*N.A.*	ECO Carbon footprint assessment (Xing et al. 2016)	IR Inventory management for efficiency (Guha and Kumar 2018)	General supply chain network design (Xing et al. 2016)

Collaborative robot (cobot)	*N.A.*		IEM Manual processing manufacturing (craft) (Guha and Kumar 2018) Manufacturing system processing speed and efficiency (Wang 2015)	*N.A.*
Cyber-physical system	*N.A.*	IEM Machining optimisation system to improve energy efficiency (Liang et al. 2018; Li et al. 2019b) Energy system for cleaner production (Ma et al. 2019; Park et al. 2020)	IEM Product disassembly (Liu et al. 2019) Optimize maintenance schedule and improve accuracy of predicting products' remaining life (Kumar et al. 2018)	*N.A.*
Internet of Things	IR Collection of solid waste (Thurer et al. 2019)	IEM Energy saving system design of dyeing process (Park et al. 2020) IR Straw recycling system design for energy conservation (Mao et al. 2019)	IEM Smart/intelligent and green/sustainable manufacturing (Alberti et al. 2019) IR Circular strategies (Charnley et al. 2019; Ingemarsdotter et al. 2019; Garrido-Hidalgo et al. 2020) Warranty and maintenance analysis of sensor embedded products (Alqahtani et al. 2019) Recovering system of returned products (Fang et al. 2016) End-of-life product monitoring system (Garrido-Hidalgo et al. 2019) Collection of used products (Ketzenberg and Metters 2020) Quality management in product recovery (Ondemir and Gupta 2014) Smart logistics (Tran-Dang et al. 2020a, 2020b) Smart circular product-service-system (Alcayaga et al. 2019) ECO Data and knowledge sharing with supplier for eco-design (Sarkis et al. 2021)	General green supply chain framework for IoT (Manavalan and Jayakrishna 2019; Miaoudakis et al. 2020)
Machine learning	IEM Sustainable facility layout design to reduce CO2 emission (Tayal et al. 2020)	IEM Sustainable facility layout design to evaluate energy efficiency (Tayal et al. 2020)	IEM Optimization of production using machine learning analytics with big data (Cioffi et al. 2020; Zhu et al. 2021) CC	*N.A.*

			Demand forecasting (Mak and Shen 2021; Zhu et al. 2021) Consumer behavior prediction (Luo and Xu 2019) ECO User-focused sustainable product design (Rymaszewska et al. 2017)	
Digital twin	*N.A.*	ECO Energy consumption intelligent detection robotics (He et al. 2021) IR Design Reducing energy consumption of cold chain logistics	IEM Production automation system (He and Bai 2021) IR Smart and green logistics system (He and Bai 2021) Product trade-in policy design (Tozanli et al. 2020)	*N.A.*
Blockchain	ECO LCA for sustainability (Zhang et al. 2020) CC Environmental behavior promotion (Esmaeilian et al. 2020)	ECO LCA for sustainability (Zhang et al. 2020) Transparent supply chain (Baumers et al. 2013; Hastig and Sodhi 2020) Green certification in distributed renewable energy (Zhao et al. 2020)	ECO LCA for sustainability (Leng et al. 2020; Zhang et al. 2020) Visibility across the entire product lifecycle (Esmaeilian et al. 2020) IEM Collaborative warehouse management (Esmaeilian et al. 2020) Using environmentally friendly materials in product (Guo et al. 2020) IR Enabled “right to repair” practices (Kouhizadeh et al. 2021) Recycling of products (Saberi et al. 2018; Benniche 2019) Waste management traceability (Gopalakrishnan et al. 2021) GP Resource sharing (Sarkis et al. 2021) CC Consumer information capture (Wang et al. 2021) Design of incentive mechanisms and tokenization to promote consumer green behavior (Esmaeilian et al. 2020)	Supply chain data sharing (Wang et al. 2021); Barriers of adoption behaviour (Saberi et al. 2019; Choi et al. 2020; Varriale et al. 2020); Sustainability monitoring and reporting performance across supply chain networks (Esmaeilian et al. 2020); Benefits of adoption in sustainable supply chain (Varriale et al. 2020);

4.2 Diffusion of innovation perspective

For innovation to diffuse, it starts with an initial few who are open to new ideas or technologies such as GSCI, and adopt them for use. The diffusion process of GSCI usually starts with industry leaders which are resourceful and open to new practices. These early adopters will showcase the benefits of innovation adoption and innovation will diffuse to the other categories of adopters from early and late majority to laggards and non-adopters (Rogers 2003). However, diffusion of GSCM happens due to the external requirement (i.e., customers or regulations) and could rapidly happen in industries. From the diffusion of innovation perspective, the issue of GSCI adoption is not to mobilize the movement of firms from one adopter category to another, but to streamline the GSCI to satisfy the needs of supply chain partners in different categories due to their varying roles, positions, resources availability, and responsibilities in the supply chains. There are also several innovation characteristics that can determine the success of GSCI diffusion, including observability, relative advantage, compatibility, trialability, and complexity of the GSCI adoption, which can explain variations of adopting GSCI among these adopter categories. The innovators or early adopters, which are usually large and resourceful enterprises, are the leaders or change agents to promote the technology applications and influence other supply chain parties for GSCI adoption. As early adopters, there can be first-mover advantages of adopting GSCI in cost-efficiency and corporate reputation due to greener operations for supply chain activities. Leading companies in GSCI can summarize and demonstrate their best practices to later GSCI adopters in their supply chains to augment their advantages relative to other rival supply chains so as to stay ahead of the competition.

4.3 Institutional perspective

In addition to the cost-efficiency and diffusion perspectives, there are different factors in the supply chain, including the cultural, social, and regulatory environments that can cause firms to adopt (or not adopt) GSCI. Beyond economic incentives, firms are under pressure to adopt innovation practices such as GSCI and make them visible to other parties as being proper and appropriate for the legitimacy purpose to stay in the supply chain. There are three forms of institutional forces, namely coercive, mimetic, and normative forces, that create isomorphic behaviours in organizational processes (Dimaggio and Powell 1983). GSCM and GSCI follow similar institutional forces to be adopted by firms. The institutional perspective explains how firms in the supply chain secure their legitimacy by conforming to the rules and norms of the institutional environment to survive their supply chain operations. In view of the technical advancement in supply chain operations, it becomes a legitimate action to adopt related GSCI for conformance with the practices of other supply chain partners due to the coercive forces from the leading firms for compliance, mimetic forces from supply chain partners to replicate their success path, or normative forces as the threshold standard in supply chain operations. Indeed, many firms adopt digital technologies, including GSCI, seeking to keep pace with technological trends or to provide rapport congruent with supply chain practices. Considerations for cost efficiency, targeted operational improvements, and plan for digital technological deployment can be secondary in the innovation adoption decision process.

4.4 Resource-based perspective

By developing a set of unique resources or capabilities, firms can create cost and service advantages to compete in their supply chain operations. This resource-based perspective argues that such resources that are inimitable, non-substitutable, rare, and valuable have the potential to generate advantages for firms to compete (Barney 1991). As firms vary in their resources, the differing resource levels over time will sustain the competitiveness of firms. From the resource-based perspective, GSCM adoption requires firms with resources and capabilities in technologies and supply chain cooperation, integration, and coordination to deal with environmental-related issues. However, GSCI adoption requires firms with the GSCM resources and capabilities, plus innovation capability to acquire, use, and optimize digital technologies in GSCM. Adoption of GSCI and related technologies with the above unique resource attributes collectively deployed can create organizational capabilities for upgrading supply chain operations. While adopting GSCI alone can create value, deployment of GSCI in the five GSCM dimensions with complementarity superior to the competition can be unique capabilities to drive performance gains. Such capabilities will enable firms to better utilize their assets and coordinate supply chain activities with great ability to improve productivity and satisfy market needs. As the resources and capabilities brought by GSCI are valuable for competitive advantages, firms are motivated for GSCI adoption and diffuse the technologies for supply chain operations to create value and make these capabilities more inimitable over rivals for sustained competitiveness. Nevertheless, innovation adoption can be costly to afford, particularly for those firms in smaller operations sizes and scales without financial resources to invest. Despite their desire for greener supply chain operations with GSCI, the lack of resources and capability to adopt innovation practices are critical hurdles to overcome in the adoption decision.

4.5 Resource-dependency perspective

Further to having GSCI as unique resources to compete, firms depend on other supply chain parties to survive and succeed. The resource-dependency perspective explains how firms exploit the dependencies on other parties (or other parties on them) for resources acquisition to compete (Pfeffer and Salancik 1978). In GSCM, there are activities dependent on the inputs from participation of upstream (e.g., eco-design and green purchasing) and downstream (e.g., resources recovery) partners to execute. To cope with the evolving market and regulatory requirements for environmental protection, firms depend on other supply chain parties to perform activities in different GSCM dimensions and tackle uncertainties. In doing so, it requires exchanges of resources and collaboration between supply chain partners to adopt and diffuse GSCI for success. Firms lacking the technological advancements to green their supply chain operations will seek to establish relationships with others to acquire the needed resources such as digital technologies on AI and Blockchain skills. To reduce uncertainties for the greater chance of success, firms will proactively solicit participation of supply chain partners to ensure consistency and compatibility of the GSCI related technologies deployed. One potential risk to leverage resources of supply chain partners for GSCI adoption is unwanted information disclosure or even leakage of operational secrets, which can put the adopter firms in unfavourable position on negotiation and bargaining power for GSCM activities such as cost and benefit sharing.

5. GSCI challenges and opportunities

Due to the globalization of production and marketing activities, we have seen a growing number of multi-national enterprises and many smaller-sized firms are joining the bandwagon in recent years. The complexity of coordinating greener supply chain activities increases with more operational locations internationally. Adopting GSCI can enhance transparency of the supply chain operations and decision making of related activities such as internal environmental management and eco-design for products among partners across different countries. Meanwhile, there are incoming environmental regulations and policies for compliance in different countries. For example, the German SC law was passed on June 11, 2021 to be enacted starting January 2023 will motivate firms, especially German firms or those operating in Germany to use digital technologies to trace social and environmental practices of their suppliers, including low-tier suppliers. The China's target for carbon peak by 2030 and carbon neutrality by 2060 will urge firms to monitor energy consumption through the whole supply chain networks. In managing the global supply chain with the emerging environmental requirement, GSCI adoption can help save the communication and monitoring costs for coordinating green operations among partner firms, but the issue of information misuse (e.g., disclosure to unintended parties) needs a solution.

There are also other challenges to overcome for GSCI to diffuse. For instance, there is resistance from managers at the upstream supply side to adopt digital technologies due to their fear of practices change and more responsibility to ensure accurate works due to increased transparency in the supply chain processes. Internally, different organizational units (e.g., environmental management, supply chain operations, technology development) may also shift responsibility to take up the leading role of planning and executing GSCI adoption, and the coordination of related tasks and responsibilities can be difficult with resistance causing delays or even termination. An implementation framework to guide the planning and measurement of digital transformation for GSCM is helpful to tackle these issues in the adoption process. For instance, some firms have established or plan to establish GSCI-related systems, but they know little about where to put.

Looking into the future, there are plentiful opportunities to extend this line of studies. GSCI has been adopted in different manufacturing enterprises at the varying degree, and there are different factors (e.g., institutional, operational, regulatory) and theoretical explanations for the adoption variations. Future studies can investigate the antecedent factors and barriers influencing GSCI adoption and focus more on service operations as many service-based enterprises such as those in shipping and transport logistics are leveraging technological innovations for enhanced efficiency and environmental protection (Yin et al. 2021). For technological applications to bring performance benefits for supply chain management activities, it is important that the enabling information flows are connected among involved partners to streamline the processes. Further research can explore how and why various mechanisms (e.g., centralized vs. decentralized supply chain structure) can promote diffusion of GSCI in the supply chains. In doing so, an assessment framework for evaluating the different dimensions of adopting GSCI and the key performance indicators for monitoring the progress will be useful to facilitate the diffusion processes.

One major concern for enterprises in GSCI adoption is the performance value of the investment. The performance value includes both tangible (e.g., better facilities and infrastructure) and intangible (e.g., customer loyalty and corporate reputation) benefits as well as short-term (e.g., stock price) and long-term gains (e.g., efficiency and productivity). To build confidence in GSCI investment, firms need to investigate the performance value of GSCI adoption. The performance contingencies on both internal (e.g., ownership type) and external (e.g., supply chain complexity) factors causing performance variations of GSCI adoption are also worthy of further research explorations. In addition to empirical validation and anecdotal case illustration, the performance value of GSCI can be evaluated to cover the different parties in supply chain activities, including customers, employees, suppliers, government and non-government organizations, and the society at large.

6. Implications and Conclusions

There are growing studies and reported practices of GSCM, particularly in the last decade, but research on innovation for GSCM is lacking in the literature. This study examines the new paradigm in the evolution of GSCM that emphasizes digital technologies in enabling the implementation of GSCI and attainment of GSCM performance goals. In applying digital technologies to improve the five GSCM dimensions, this concept of GSCI is discussed with the following academic contributions. It complements and extends the literature on GSCM, emphasizing the value of innovation for greening supply chain activities (Abu Seman et al. 2019), which provides examples of how digital technologies can be leveraged for GSCM to attain better performance outcomes. Researchers can extend this line of research on the theoretical development of GSCI adoption and performance contingencies. Investigating innovation, particularly the digital transformation of GSCM is critical considering the fast-paced technological development for enterprises to stay on a technology-enabled supply chain for environmental compliance. In doing so, enterprises need to take proactive actions for integrating digital technology applications in the different implementation facets of GSCM. This study provides the first step to understand such integrative efforts and promote theoretical development for GSCI adoption in today's digitalized business operations. Meanwhile, there are also challenges and opportunities for adopting GSCI. Among these, the resistance internally in organizational units due to fear of changes and externally among supply chain partners due to lack of related knowledge and financial resources to afford the technological investments are major hurdles to overcome. It is useful to highlight the benefits of GSCI internally and promote stakeholder engagement with incentives (e.g., recognitions, subsidy) to diffuse the adoption. The increasing market and regulatory requirements for environmental preservation are indeed operational pressures for enterprises to conform. Such pressures can be taken as positive forces to convince these internal and external parties in supply chains to implement GSCI, which can bring performance value such as better pollution control and higher resources efficiency to meet the public environmental expectation for supply chain activities.

From our literature findings, GSCI appears to benefit GSCM implementation and performance outcomes, which is consistent with many previous studies on the value of information technology for inter-organizational information integration (Wong et al. 2015). As such, GSCI has emerged as a new paradigm of GSCM for performance enhancements. Nevertheless, the effects of GSCI on performance in both short (e.g., market value of firms) and long (e.g., return on investment) are yet to be proven empirically, which need future research evidence. Since GSCI is an emerging concept, more research investigation is desired to explain how GSCI practices can be effectively pursued to better achieve strategic and operational goals for enterprises and across supply chain partners. More theoretical analyses integrating organizational theories to explain the mechanisms for GSCI adoption, and the performance contingency factors such as industry type (service vs manufacturing) and nature (B2B vs B2C), firm size (large vs small), ownership (private vs public), operating environment (high vs low uncertainty) and so on are promising directions to extend this research stream.

Furthermore, there can be alternative explanations for GSCI adoption and diffusion other than the five organizational theories examined in this study. We refer readers to an earlier research paper for identifying possible organizational theories to analyze the antecedents and consequences of GSCI adoption (Sarkis et al. 2011). We expect more new applications for GSCI with emerging digital technologies in years ahead which are not possible for this paper to fully cover. Their applications for GSCI at both strategic (e.g., customer-supplier coordination models for eco-design) and operational (e.g., investment recovery through better connectivity of devices) levels and their shorter- and longer- term cost and benefit implications are worthy of further investigations.

There are several limitations of this study in examining GSCI concept and practices. While we identify ten major digital technologies for GSCI, the technology field is evolving with the new development that literature evidence cannot fully cover most recent developments such as 5G-powered supply chain automation. Literature evidence in the area of 5G-powered supply chain adoption and implementation challenges is very scarce (Dolgui and Ivanov 2021), not to mention the applications for GSCM. Investigating emerging and evolving digital technologies for GSCI and the new features and performance value created can be novel research topics in this area.

Practically, this study helps managers better understand the GSCI concept and practice, realize the potentials for GSCM, and promote GSCI adoption in workplace. More research efforts on the applications and value of GSCI are encouraged to unravel the innovation for GSCM. Managers are advised to pay attention to the rapidly-changing digital development in business operations, which calls for appropriate implementation framework and performance evaluation to guide GSCI development. It is important that enterprises are aware of the different digital technology options for greening the supply chains. They also need to make proper evaluation for the digital needs to enhance different GSCM dimensions and ensure resources availability to support digital technology applications, and monitor the GSCI adoption process. Managers are advised to engage supply chain partners to deploy digital technologies for greater GSCM performance. Developing a roadmap and key performance indicators to guide GSCI diffusion in supply chains can be useful in the process.

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Appendix. Digital technologies and descriptions

Enabling technology	Descriptions
3D printing	A hard technology which is used to fabricate three-dimensional objects based on the digitally controlled deposition of successive layers of material until a final structure is created. It is also named as additive manufacturing. 3D printing has been applied in manufacturing and medical industries (i.e., rapid prototyping) and social cultural sectors (i.e., cultural heritage) *Source:* The economist, https://www.economist.com/technology-quarterly/2013/09/05/3d-printing-scales-up
Artificial intelligence (AI)	A soft technology used in the study of "intelligent agents": any system that perceives its environment and takes actions that maximize its chance of achieving its goals (Poole et al. 1998). AI applications include advanced web search engines (i.e. Google), recommendation systems (used by YouTube, Amazon and Netflix), understanding human speech (such as Siri), self-driving cars, automated decision-making and competing at the highest level in strategic game systems (such as chess Alpha Go).
Big data	A soft technology used in the field that treats ways to analyze, systematically extract information from, or otherwise deal with data sets that are too large or complex to be dealt with by traditional data-processing application software (Hilbert and López 2011). Data with many fields offer greater statistical power, while data with higher complexity (more attributes or columns) may lead to a higher false discovery rate. Big data was originally associated with three key concepts: volume, variety, and velocity.
Cloud computing	A soft technology used in analysis of on-demand availability of computer system resources, especially data storage (cloud storage) and computing power, without direct active management by the user (Montazerolghaem et al. 2020). Cloud computing relies on sharing of resources to achieve coherence and economies of scale, typically using a "pay-as-you-go" model which can help in reducing capital expenses but may also lead to unexpected operating expenses for unaware users.
Collaborative robot (cobot)	A hard technology enabling a robot intended for direct human robot interaction within a shared space, or where humans and robots are in close proximity. Cobot applications contrast with traditional industrial robot applications in which robots are isolated from human contact. There are four levels of collaboration between robots and human beings: co-existence, sequential collaboration (do not work on a part at the same time), cooperation (work at the same time), and responsive collaboration (robots response in real-time to the movement of human worker). *Source*: The manufacturer, https://www.themanufacturer.com/articles/i-cobot-future-collaboration-of-man-and-machine/
Cyber-physical system	A soft technology of computer system in which a mechanism is controlled or monitored by computer-based algorithms. In cyber-physical systems, physical and software components are deeply intertwined, able to operate on different spatial and temporal scales, exhibit multiple and distinct behavioral modalities, and interact with each other in ways that change with context. *Source*: US National Science Foundation, https://www.nsf.gov/pubs/2010/nsf10515/nsf10515.htm
Internet of Things (IoT)	A connectivity technology using physical objects (or groups of such objects) that are embedded with sensors, processing ability, software, and other technologies, and that connect and exchange data with other devices and systems over the Internet or other communications networks. *Source:* Internet of Things Global Standards Initiative, https://www.itu.int/en/ITU-T/gsi/iot/Pages/default.aspx
Machine learning	A soft technology of data analysis that automates analytical model building. It is a branch of artificial intelligence based on the idea that systems can learn from data, identify patterns, and make decisions with minimal human intervention. *Source*: "What is Machine Learning?". www.ibm.com. Retrieved 2021-08-15.
Digital twin	A connectivity technology of virtual representation that serves as the real-time digital counterpart of a physical object or process. Digital twins are the result of continual improvement in the creation of product design and engineering activities. *Source:* The Forbes website (https://www.forbes.com/sites/bernardmarr/2017/03/06/what-is-digital-twin-technology-and-why-is-it-so-important/#120111ec2e2a)
Blockchain	A soft technology generating a growing list of records, called blocks, that are linked together using cryptography. Blockchains are typically managed by a peer-to-peer network for use as a publicly distributed ledger, where nodes collectively adhere to a protocol to communicate and validate new blocks. Block chain has been applied in smart contract, supply chain finance, energy trading, etc. *Source:* The New York Times (https://www.nytimes.com/2016/05/22/business/dealbook/crypto-ether-bitcoin-currency.html)

Note: Adapted from sources including UNIDO's Industrial Development Report 2020