Electronic Markets (2025) 35:33
https://doi.org/10.1007/s12525-025-00779-7

RESEARCH PAPER

Bridging carbon data's organizational boundaries: toward automated data sharing in sustainable supply chains

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Received: 11 July 2024 / Accepted: 2 April 2025

Abstract
The accounting of greenhouse gas (GHG) emissions is seen as an essential element to mitigate global climate change. Robust "carbon accounting" (CA) is supposed to enable the quantification of greenhouse gas (GHG) emissions and identification of reduction potential, thereby enabling CO2-adaptive decision-making for various stakeholders, including organizations and end-users. In this regard, digital technologies can not only improve the efficiency and accuracy of CA in various ways, but also support the effective sharing of carbon data along supply chains. However, the current use of digital technologies in CA practices is often limited to an intra-organizational perspective. Extending the application of digital technologies for automated data sharing beyond organizational boundaries appears promising for addressing supply chain emissions accounting and potentially closing today's huge Scope 3 emissions accounting gap. This is especially relevant since upstream Scope 3 emissions can cause up to 80% of the total GHG emissions for most manufacturing industries. Furthermore, automated data sharing beyond organizational boundaries can provide the necessary foundation for fostering automation in supply chain management based on sustainability metrics. In this paper, we provide a comprehensive framework for automated data sharing in supply chains to support CA within and beyond organizations' boundaries. Our findings suggest that the use of a combination of digital technologies can not only strengthen CA practices within organizations and their supply chain, but also foster the development of digital supply chain ecosystems, allowing automated sharing of data for a plethora of use cases.

Keywords Carbon accounting · Data sharing · Digital decarbonization · Grounded theory · Supply chain automation · Sustainable supply chain

JEL Classification Q55

Introduction

Supply chain automation has emerged as a promising tool for increasing efficiency across multi-tier supply chain networks by automating information flows among different actors (Flechsig et al., 2022; Xu et al., 2024). Beyond efficiency gains, automated supply chain systems enhanced by digital technologies, such as applying Artificial Intelligence (AI) and robotic process automation for automated ordering with organizations' Enterprise Resource Planning (ERP) systems play a key role, promise to improve the network's responsiveness and resilience while reducing operational costs and human errors (Flechsig et al., 2022; Richter et al., 2022). However, some organizations hesitate to implement automation tools such as automated ordering due to poor data quality (Berneis et al., 2024), underscoring the need for a solid data foundation for supply chain automation and associated digital technologies to be a valuable asset for supply chain management.

In the light of global decarbonization efforts, markets and regulators will demand far more information about products, organizations, and their supply chains in the future, posing significant challenges, including the availability and quality of the data. In particular, they increasingly require organizations to demonstrate sustainable practices both in

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their organizations and across their supply chains (Negri et al., 2021): First, an increasing number of customers demand more sustainable products and services as well as more transparency in this regard. Second, investors are prioritizing investing in companies that demonstrate robust sustainability efforts and banks are increasingly taking Environmental, Social and Governance (ESG) criteria into account when granting debt capital (Gramlich et al., 2024). Third, existing and anticipated environmental regulations are becoming stricter, as evidenced by the Corporate Sustainability Due Diligence Directive (CSDDD). It was approved by the European Parliament in April 2024 and requires comprehensive sustainability reporting across supply chains (European Parliament, 2024). This raises the question whether current sustainable supply chain practices will be sufficient to meet new obligations (Müller et al., 2023).

Against this background and the fact that GHG emissions are at the center of many sustainability practices, researchers already suggest that organizations may gather precise data about all GHG emissions associated with their products and services (e.g., Meinrenken et al., 2020 or Zhang et al., 2022). Supply chain emissions often represent the majority of emissions in product carbon footprints. For instance, Meinrenken et al. (2020) illustrate based on 866 products from 16 different product categories that indirect emissions accounted for an average of 64 % of the carbon footprint, and Huang et al. (2009) state that upstream Scope 3 emissions (i.e., emissions from entities not controlled or owned by an organization itself) account for 70–80 % of the total carbon footprint analyzed for most manufacturing industries. Therefore, a critical challenge arises in the measurement of indirect emissions from organizations' supply chains (i.e., providing a sound data foundation) (Stechemesser and Guenther, 2012). Organizations often rely on industry averages instead of primary data, which refers to directly measured or observed data, for their calculations. This reliance on generalized figures can obscure the true extent of emissions and diminish incentives for individual organizations to strive for emissions under these averages (Stenzel and Waichman, 2023). Such practices not only reduce the effectiveness of Carbon Accounting (CA) in identifying and exploiting GHG saving potentials but also risk contributing to greenwashing, where the environmental impacts are understated or misrepresented (Dorfleitner and Utz, 2023). The use of industry average data instead of primary data sources often stems from a lack of detailed and reliable emissions data sharing within organizations and along their supply chains. While collecting these primary data is possible, for example, using smart meters for electricity monitoring (Zhou and Brown, 2017), several challenges hinder the sharing of primary data related to GHG emissions. These include concerns about privacy regulations, lack of incentives, fear of reputational damage from high emissions, or the need to protect competition-relevant data (Heeß et al., 2024; Stenzel and Waichman, 2023). Addressing these challenges and enabling precise CA beyond organizations' boundaries can enable CO2-adaptive decision-making (e.g., shifting energy consumption to times when it produces fewer emissions) and accelerate decarbonization (Körner et al., 2023). Furthermore, such practices are the cornerstone for increasing automation in sustainable supply chain management that not only optimizes for traditional metrics like costs but also incorporates emissions data.

To further facilitate supply chain automation, a variety of digital technologies seem promising, as outlined, for example, by Ciccullo et al. (2022) or Rachana Harish et al. (2023): In particular, a combination of digital technologies may be suitable to address the challenges outlined above and provide the foundation for automated data sharing in supply chains to support CA within and beyond organizations' boundaries. As we will delineate in this paper, such data sharing can provide the basis for enabling CO2-adaptive decision-making in organizations and automated supply chain management based on sustainability data. This Information Systems (IS) centered approach to environmental challenges aligns with the growing field of Green IS, which can be defined as "the use of information systems to achieve environmental objectives" (Dedrick, 2010). Calling on Watson et al.'s (2010) idea of improving information flows for sustainability, only recently scholarly work started to actively investigate how digital technologies can enhance sustainable data sharing in supply chains (Babel et al., 2024; Heeß et al., 2024; Krasikov and Legner, 2023).

However, the precise application of digital technologies in automated data sharing in supply chains is still in an early stage. Despite the existence of specific approaches in practice (e.g., Catena-X's Product Carbon Footprint, EY's OpsChain ESG, SAP's climate action solutions, or Siemens' SiGREEN), the body of academic knowledge lacks a comprehensive framework regarding how digital technologies can facilitate data sharing in supply chains and support current CA practices, particularly in addressing the complexities of indirect emissions. Hence, in this research paper, we aim at providing guidance for researchers as well as industry experts and policymakers by answering the following question:

How can digital technologies support automated data sharing in supply chains and hence carbon accounting within and beyond organizations' boundaries?

The contribution of our paper is two-fold. First, we argue that a comprehensive framework is necessary for organizations to effectively design and evaluate their data-sharing practices regarding CA. As the topic spans several domains, including (Green) IS, (Sustainable) Supply Chain Management, and (Ecological) Economics, we deploy a Systematic Literature Review (SLR) to rigorously analyze and synthesize the diverse body of knowledge across these fields. Our detailed analysis of the current literature aids in the development of more efficient and transparent data sharing in supply chains to support CA. By doing so, our paper provides a pathway for the integration of these technologies into existing CA practices, highlighting the role of automated data sharing as a key enabler. Consequently, this effort contributes to the overarching goal of decarbonization, facilitating enhanced management and reporting of carbon emissions across various organizations and their supply chains. Second, by conducting a systematic review of different concepts and technologies within CA, we highlight potential avenues for future research in automated data sharing between organizations for CA. The presentation of our results allows for categorizing existing approaches and identifying potential implications of emerging technologies that can facilitate the further development of digital CA in research and practice, especially beyond organizations' boundaries, possibly paving the path toward a digital carbon management ecosystem. Moreover, we discuss how our results relate and contribute to ongoing developments in supply chain automation.

We answer our research question by following a grounded theory approach based on an SLR. Thereby, we provide a comprehensive framework for automated data sharing in supply chains to support CA. The remainder of this paper is structured as follows: We discuss relevant literature in the "Background and related literature" section, outlining the status quo and current advances in Green IS and digital decarbonization, data sharing and automation, and CA in supply chains. Next, we outline our methodology in the "Methodological approach" section, which includes an SLR and follows the grounded theory approach of Corbin and Strauss (1990). We present our framework in the "Results" section. In the "Discussion" section, we discuss our findings and highlight the implications, formulated as two developments — toward twin transformation and toward an ecosystem perspective — as well as two corresponding implications we derive based on these developments. We conclude in the "Conclusion" section with our main contributions, the limitations of this paper, and directions for future research.

Background and related literature

In this section, we give an introduction to the relevant work and research streams and provide a short overview of the relevant literature and background for our work. First, we outline recent developments in Green IS and digital decarbonization. Second, we illustrate data sharing and automation in supply chains. Last, we shed light on current efforts in supply chain CA.

Green information systems and digital decarbonization

The research stream on Green IS examines, designs, and models digital solutions aimed at achieving a sustainable future and is widely recognized for its interdisciplinary nature (Melville, 2010; vom Brocke et al., 2013). The literature on Green IS encompasses a wide range of applications, including sustainable logistics and supply chain management (Qu and Liu, 2022), the mobility sector (Ketter et al., 2023), the energy sector (Watson et al., 2010), and circular economy (Zeiss et al., 2021). In the light of the increasingly pressing need for approaches to mitigate climate change, there has been increasing attention among Green IS scholars regarding the imperative to accelerate the reduction of GHG emissions (i.e., digital decarbonization) (Körner et al., 2023; Heeß et al., 2024; Zampou et al., 2022).

Initially, the primary role of Green IS was perceived as a tool at the intra-organizational and individual levels, designed to support organizations by facilitating the adoption of new sustainable processes and practices and to drive behavioral change. By doing so, Green IS has been shown to contribute to sustainable and economic outcomes (Melville, 2010; vom Brocke et al., 2013). Recent research in Green IS has expanded the scope to include market-based use cases for digital decarbonization efforts. These include, for example, leveraging the potential of digital technologies in carbon markets to improve identity management and enhance efficiency, e.g., through automated transactions in carbon trading via smart contracts (Li and Li, 2021). Only recently, Green IS scholars outlined the significant role of data in sustainability efforts (Püchel et al., 2024). Green IS also explores the technical implementation of digital carbon credits, which serve as a tool for carbon offsetting, and similar digital assets, such as renewable energy credits and proofs of origin. Existing literature acknowledges the necessity of digital credit schemes that enhance transparency and traceability for organizations (e.g., Chakraborty et al., 2022) and end consumers (e.g., da Cruz et al., 2020). Furthermore, current research addresses regulatory concerns like privacy in this context (e.g., Babel et al., 2022). Additionally, it underscores the importance of digital CA, as, e.g., highlighted by Velazquez Abad and Dodds (2020) in the context of green hydrogen and Körner et al. (2024) in the building sector. However, research in this field is still emerging, likely driven by pressure from policy and market stakeholders seeking effective solutions for reducing GHG emissions, and lacks an overarching framework for automated data sharing in supply chains, especially when addressing the complexity of indirect emissions along and across supply chains.

Data sharing and automation in supply chains

Supply chain automation, the use of digital technologies to automate processes and workflows across supply chains, has become increasingly important as organizations seek to improve efficiency and reduce manual intervention (Richter et al., 2022; Xu et al., 2024). Such automation aims to replace human-led processes with machine or software solutions and spans the planning, control, and execution of physical, information, and financial flows within supply chains (Nitsche et al., 2021). Particularly on the software side, which represents the main focus of this paper, supply chain automation relies heavily on effective data sharing along supply chains (i.e., inter-organizational data sharing). For decades, researchers have highlighted inter-organizational data sharing as critical to competitive advantage (Redman, 1995; Otto and Jarke, 2019) and as particularly critical to achieving good performance and innovation in the digital age (Difrancesco et al., 2022; Zhou and Benton, 2007). Such data sharing can reduce the bullwhip effect, which occurs when fluctuations in customer demand cause increasingly large fluctuations in orders and inventories as you move up the supply chain (Chen et al., 2000). In addition, inter-organizational data sharing is an integral part of value co-creation, which is defined as the joint activities of different parties involved in direct interactions that aim to contribute to the value created for one or more of these parties (Grönroos, 2012; Prockl et al., 2017; Ranjan and Read, 2016).

While the benefits of automated data sharing regarding collaboration in supply chains are clear, many organizations refrain from doing so, leaving the majority of (industrial) data unused (Jussen et al., 2023). Aside from the initial financial investment required as well as a lack of mutual trust, communication, and understanding (Leckel and Linnartz, 2023), one of the largest challenges to automated data sharing is collecting all relevant data in sufficient quality in order to share them effectively. A robust, high-quality data foundation for all related stakeholders would be necessary for organizations to automate their supply chains, as the full potential of such software automation can only be realized when implemented holistically across several divisions and supply chain partners (Ajiga et al., 2024; Nitsche et al., 2021; Xu et al., 2024).

In this light, digital technologies and data quality can positively influence the intensity of data sharing and, hence, automated management of supply chains (Baihaqi and Sohal, 2013). As we will outline in this paper, recent research in this area explores the use of various digital technologies and concepts, such as AI, DLT, and PETs, to address current challenges that hinder effective data sharing, for instance data misuse, privacy concerns, and insufficient data quality (e.g., Jussen et al., 2023; Tsolakis et al., 2023; Wang et al., 2020). To provide a brief, non-exhaustive overview for readers, we illustrate the technologies and digital concepts that current literature considers promising for inter-organizational data sharing and supply chain automation in Table 1. Current literature on CA hardly focuses on the context of inter-organizational data sharing and supply chain automation. Such data- and automation-driven perspectives on CA can, however, help accelerate decarbonization and enable more sustainable supply chains (Ajiga et al., 2024; Krasikov and Legner, 2023; Püchel et al., 2024).

Supply chain carbon accounting

GHG or carbon emissions accounting includes the accounting, valuation, and monitoring of GHG emissions and their impacts at each stage of the value chain (Stechemesser and Guenther, 2012). On entity scale — which represents the main scope of this paper — CA mainly focuses on emissions associated with enterprises and other organizations (Damsø et al., 2016). For the former, the term corporate CA is well established in CA literature (He et al., 2022). The GHG Protocol Corporate Accounting and Reporting Standard represents the most widely used framework for corporate CA. It distinguishes three scopes of emissions: Scope 1 encompasses direct emissions from sources that are owned or controlled by the organization, while Scope 2 emissions refer to the generation of purchased electricity consumed by the organization, and Scope 3 includes all indirect emissions not covered in Scope 1 and 2, arising due to upstream and downstream activities along the supply chain of an organization (WRI and WBCSD, 2004). The concept of Monitoring, Reporting, and Verification (MRV) offers a more granular and procedural framework of CA principles (Bellassen et al., 2015; Olczak et al., 2022; Tang et al., 2018). In current MRV practices, monitoring generally refers to estimating or measuring GHG emissions, reporting involves recording, aggregating, and reporting GHG emissions to authorities, and verification typically involves ensuring compliance with specific guidelines through a third-party assessment (Bellassen et al., 2015). By conceptualizing, implementing, and evaluating approaches for digital MRV, researchers, industry experts, and policymakers can contribute to advancing CA in various ways. These advancements can include enabling greater automation, providing more precise data, and offering increased transparency (Dorfleitner and Braun, 2019; Olczak et al., 2022; Tang et al., 2018). We note that there is a growing subset of research on how to implement or improve digital MRV, see, for example, Woo et al. (2020), who outline a digital framework for MRV in the building sector, or Kim and Baumann (2022), who propose an ontology and blockchain-based MRV system.

Efforts in the sustainable supply chain literature illustrate the need for integrating an inter-organizational perspective into the intra-organizational view on low-carbon efforts (de Sousa Jabbour et al., 2021). CA along the supply chain

Table 1 Digital concepts and technologies that are discussed in this paper

Digital concept or technology	Description and application within the context of data sharing and carbon accounting in supply chains	Exemplary references
Artificial Intelligence (AI)	Computational systems capable of performing tasks requiring human intelligence, such as learning, reasoning, and problem-solving. In the context of supply chains and carbon accounting, AI can enable automated data analysis, validation of emissions data, and optimization of data collection processes across organizations	Tsolakis et al. (2023)
Distributed Ledger Technology (DLT)	A system that maintains an immutable record of transactions across a distributed network of participating nodes. In supply chains, DLT-like blockchains can, among others, create transparent and verifiable audit trails for carbon data	Diniz et al. (2021)
Data Space	A federated data infrastructure that enables sovereign data sharing between participating organizations in digital ecosystems. In supply chains and carbon accounting, data spaces can facilitate the controlled exchange of emissions data while preserving data sovereignty, enabling organizations to share carbon-related information without losing control over their data	Ito et al. (2022)
Privacy Enhancing Technology (PET)	Technology designed to protect data privacy while allowing processing and analysis. In supply chains, PETs, such as Zero-Knowledge Proofs (ZKPs) or Homomorphic Encryption, allow organizations to share and analyze sensitive emissions data while maintaining confidentiality	Babel et al. (2022)
Self-Sovereign Identity (SSI)	A digital identity paradigm where users and organizations maintain sovereignty over their identity data and credentials. In supply chain contexts, SSI can enable organizations to selectively share verifiable emissions data while maintaining data sovereignty	Mandaroux et al. (2021)
Smart Contract	Self-executing software programs that automatically enforce predefined rules and agreements. In carbon accounting, smart contracts can automate the verification and reporting of emissions data between supply chain partners, reducing the need for intermediaries while ensuring compliance	Sadawi et al. (2021)
Token	A digital unit that can represent any form of value or asset, primarily used on blockchain systems. In supply chains, fungible tokens (i.e., tokens representing interchangeable units) can represent assets, such as equal emission allowances, while non-fungible tokens (i.e., tokens representing non-interchangeable units) can be used to distinguish the origin of emissions	Babel et al. (2022)

for the total emissions related to a specific event, organization, individual, or product is typically referred to as a "carbon footprint" (Ju et al., 2022; Wang et al., 2020). Product Carbon Footprints (PCFs) are particularly influential in sustainability-based decision-making for organizations and consumers and represent a function of a product's entire life cycle (Meinrenken et al., 2020). As such, PCFs demand information about products and their entire supply chain (i.e., encompassing Scope 1, 2, and 3 according to the GHG protocol).

Against this background, we note that there are many industry-, policy-, and scholarly-driven efforts in digital decarbonization and CA to facilitate sustainable practices in organizations and within supply chain management in particular. However, we also note that research currently lacks a comprehensive framework for automated data sharing in supply chains to support CA within and beyond organizations' boundaries. With developing such a framework, we aim at effectively supporting the implementation of more efficient and transparent data-sharing practices in the area of CA, categorize existing approaches, and identify potential impacts of digital technologies that could further advance digital CA in both research and practice, especially across organizations' boundaries.

Methodological approach

To accurately assess the current state of digital technologies in CA as an enabler for data sharing in supply chains and to provide a holistic basis for answering our research question, we conduct an SLR. On the basis of this SLR, we use a grounded theory approach to develop our framework for digital CA to provide guidance to scholars, industry experts, and policymakers on how to achieve robust digital CA in the context of supply chain automation. In this section, we outline our methodological procedure.

Systematic literature review

We perform our SLR according to the methodology outlined by Webster and Watson (2002). This allows for a systematic examination of relevant outlets, ensuring a comprehensive and integrative view on the literature related to our research question and building on existing knowledge, as recommended by vom Brocke et al. (2015). We summarize our SLR process in Fig. 1.

As suggested by Kitchenham et al. (2009), the initial stage of our SLR involves a preliminary examination of key publications. This step allows us to identify essential keywords and synonyms relevant to our research question. We use these terms to develop a three-part search string: *(technolog* OR digital OR "information system" OR "green IS" OR "supply chain") AND (GHG OR emission OR carbon OR CO2) AND (trac* OR account OR MRV).*

We perform this search string on the interdisciplinary journal database Web of Science (Core Collection). Given our focus on digital technologies, we also searched the ACM Digital Library and the AIS eLibrary. We perform the search on the title and abstract. Our search includes only publications written in English, peer-reviewed, and published since 2018 to provide an overview of current and internationally relevant literature in this rapidly evolving research area. In addition, we include ArXiv to cover preprints and current research streams. Our primary search returned 6058 initial hits. We then conduct title, abstract, and full-text screening to ensure the papers' relevance. For the screening, we apply the exclusion criteria that are illustrated in Table 2.

First, we exclude publications whose title indicates that the focus is not on digital technologies and GHG emissions (e.g., papers focusing on chemical engineering, materials science, or biological processes). In the abstract search, we further exclude publications that do not address CA or related concepts, as described in the "Background and related literature" section. Thus, we exclude literature that, for example, focuses only on the aspect of carbon trading. Second, we only include publications covering digital technologies. Accordingly, we also exclude results that, for example, only provide a political or societal perspective on the topic and do not mention either digital technologies in general or a specific technology in the abstract. Using these criteria, we obtained 21 results, which we screened based on the full text. At this stage, we exclude all publications that do not include a significant contribution or discussion of both digital technologies and carbon accounting (or related concepts). In this step, we only removed one article. We further analyze the remaining 20 articles by performing a snowball search as recommended by Webster and Watson (2002). Back- and forward searches yield an additional 15 relevant articles that we include after testing them against all exclusion criteria in Table 2. Ultimately, our SLR yielded a total of 35 relevant articles.

Bibliographic and thematic analysis

As illustrated in Table 3, we sort all 35 articles derived in the aforementioned process alphabetically by the first author and summarize them with their publication year, type (i.e., journal article, conference article, or preprint), and outlet (i.e., the journal name, proceedings, or preprint database). Notably, most papers have been recently published (only one result from 2018 and none from 2019). Moreover, the majority of papers (22 out of 35) have been published in journals. These publications span a plethora of different outlets with different focuses, such as the environment (e.g., Journal of Cleaner Production), IS (e.g., Journal of the Association for Information Systems), or specific technologies (e.g., Journal of Sensors).

We further categorize our final set of papers thematically based on methodology (resp. artifact), sector, and area of analysis in Table 3. Notably, some papers (especially technology-oriented conference papers) do not provide an extensive methodology section and instead directly propose a novel framework or describe their prototype, which is why we focus on the developed artifact for these papers. Most of the papers we analyze are sector-agnostic (e.g., focusing on corporate carbon emissions in general) or focus on high-emission sectors such as energy and buildings. Furthermore, the majority of papers analyze organizations and their supply chains with some exceptions focusing mainly on (carbon) markets or individuals.

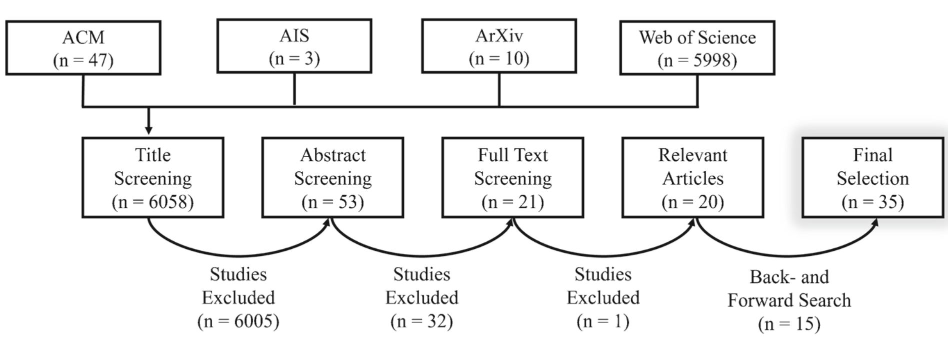

Fig. 1 Systematic literature review process

Table 2 Exclusion criteria for our systematic literature review

	#	Exclusion criteria	Description
Pre-screening	1	Language	Exclude if title is not in English
	2	Duplicates	Exclude duplicates
	3	Publication Date	Exclude if published before 2018
Title	4a	Digital Technologies	Exclude only if focus is not technology-oriented
	4b	Carbon Accounting	Exclude only if focus is not on GHG emissions
Abstract	5a	Digital Technologies	Exclude if digital technologies are not mentioned in abstract
	5b	Carbon Accounting	Exclude if carbon accounting or related concepts (e.g., MRV) are not mentioned in the abstract
Full Text	6a	Digital Technologies	Exclude if digital technologies are not a key topic in the full-text (i.e., at least one section dedicated to them)
	6b	Carbon Accounting	Exclude if carbon accounting is not a key topic in the full-text (i.e., at least one section dedicated to it)

Grounded theory

For building our framework and answering our research question, we use a grounded theory approach as specified by Corbin and Strauss (1990). Grounded theory is well-established in IS literature (Wiesche et al., 2017) as well as in supply chain literature, see, for example, Pinnington et al. (2016) or Shojaei and Haeri (2019). As illustrated by Wolfswinkel et al. (2013), grounded theory functions well in conjunction with SLRs in order to provide a more rigorous proceeding and enables a theory-based or concept-centric yet accurate review.

Following the proposed procedures and canons of Corbin and Strauss (1990) allows us to perform a systematic and inductive exploration of the research domain of digital CA. The data set for our grounded theory approach is gathered from the SLR and analyzed upon collection to avoid missing possibly salient data. The analysis involves a constant comparative method, allowing emerging themes and patterns to shape the development of theoretical constructs. We initially conducted individual coding by two researchers with regular discussions to reconcile different interpretations, merge similar concepts, and document the development of our coding. Consecutively, we supplement this process with regular discussions among all authors to validate emerging categories and their relationships. In this process, we label the data from the SLR iteratively by highlighting relevant sections of each individual paper to identify concepts that become more abstract over the course of our iterative proceeding. As the research process continues, we group the concepts that emerge from these sections into categories. We do so by finding and discussing patterns in the data based on coding as described by Wolfswinkel et al. (2013). Below we describe in more detail our approach to each coding step.

First, we perform an open coding in which we identify excerpts that are relevant to answering our research question and incorporate them into a set of categories. As described by Corbin and Strauss (1990), we proceed iteratively by questioning and discussing the categories within the author team with each new data point (i.e., each new paper) that we code. Thereby, categories that may seem highly relevant after analyzing the first few papers may be subordinated or secondary when put into context with other literature. For example, during our iterations, we include aspects such as data privacy (e.g., Heiss et al. (2023), identity management (e.g., Babel et al., 2022), and MRV (e.g., Körner et al., 2023). We ultimately exclude them as we realize that the structuring elements are data quality (e.g., Lorenzo-Sáez et al., 2022; Yan et al., 2022; Zampou et al., 2022), integration and interoperability (e.g., Guzman et al., 2019; Mandaroux et al., 2021; Schletz et al., 2022), end-to-end data flows (e.g., Babel et al., 2022; Heiss et al., 2023; Ju et al., 2022), and data governance (e.g., Diniz et al., 2021; Franke et al., 2020; Schletz et al., 2020) by coding, structuring, and discussing more papers. These categories represent recurring and core themes across most of the 35 papers we analyze (cf. Appendix A).

We then perform axial coding, identifying the interrelations between these categories and their sub-categories and properties. We proceed similarly to the open coding and iteratively include and exclude recurring and potentially relevant aspects within our four categories. For example, sub-categories where different research streams and even authors tend to use different terms for similar aspects or have different preferences, such as end-to-end integrity (e.g., Heiss et al., 2023), traceability (e.g., Sadawi et al., 2021), or transparency (e.g., Mandaroux et al., 2021), are intensely discussed and ultimately aggregated in this step.

Finally, we use selective coding to integrate and refine our main categories. For example, we rename the end-to-end data flows category to data flows, as we realize that not all sub-categories fulfill the end-to-end aspect (e.g., Tang et al., 2018). In this step, we also identify and develop the relationships between our categories as suggested by Corbin and Strauss (1990). We stop the iterative process when saturation

Table 3 Overview of the results of our structured literature review

#	Author (year)	Type	Outlet	Methodology/artifact	Sector	Area of analysis
1	Ajufo and Bekaroo (2021)	Conference Article	International Conference on Artificial Intelligence and its Applications (icARTi)	Prototype	Transport	Individuals
2	Babel et al. (2022)	Journal Article	Energy Informatics	Prototype	Energy	Organizations and Their Supply Chains
3	Chakraborty et al. (2022)	Conference Article	International Conference on Blockchain and Distributed Systems Security (ICBDS)	Prototype	Agnostic	Markets
4	Diniz et al. (2021)	Journal Article	Journal of Cleaner Production	Design Science Research	Agnostic	Organizations and Their Supply Chains
5	Franke et al. (2020)	Journal Article	Sustainability	Framework	Agnostic	Markets
6	Guzman et al. (2019)	Conference Article	International Workshop on Social Sensing (SocialSense)	Prototype	Agnostic	Individuals
7	Heiss et al. (2023)	Journal Article	IEEE Transactions on Services Computing	Prototype	Agnostic	Organizations and Their Supply Chains
8	Ito et al. (2022)	Conference Article	Annual Conference of the Society of Instrument and Control Engineers of Japan (SICE)	Prototype	Agnostic	Organizations and Their Supply Chains
9	Ju et al. (2022)	Journal Article	International Journal of Environmental Research and Public Health	Simulation Experiment	Agnostic	Organizations and Their Supply Chains
10	Kim and Baumann (2022)	Preprint	SSRN	Framework	Agnostic	Organizations and Their Supply Chains
11	Kim and Huh (2020)	Journal Article	Sustainability	Prototype	Agnostic	Markets
12	Körner et al. (2023)	Conference Article	Americas Conference on Information Systems (AMCIS)	Literature Review	Agnostic	Organizations and Their Supply Chains
13	Li et al. (2023)	Conference Article	International Conference on Public Service, Economic Management and Sustainable Development (PESD)	Framework	Energy	Organizations and Their Supply Chains
14	Li and Li (2021)	Conference Article	International Conference on Electronic Information Technology and Computer Engineering (EITCE)	Framework	Agnostic	Organizations and Their Supply Chains
15	Liu et al. (2022)	Journal Article	Engineering	Framework	Agnostic	Organizations and Their Supply Chains

Table 3 continued

#	Author (year)	Type	Outlet	Methodology/artifact	Sector	Area of analysis
16	Lorenzo-Sáez et al. (2022)	Journal Article	Urban Climate	Single Case Study	Agnostic	Markets
17	Mandaroux et al. (2021)	Journal Article	Sustainability	Framework	Agnostic	Markets
18	Müller et al. (2023)	Conference Article	Hawaii International Conference on System Sciences (HICSS)	Design Science Research	Agnostic	Organizations and Their Supply Chains
19	Muzumdar et al. (2022)	Journal Article	Journal of Cleaner Production	Mathematical Modeling	Agnostic	Markets
20	Olczak et al. (2022)	Journal Article	Environmental Science & Policy	Expert Interviews	Agnostic	Organizations and Their Supply Chains
21	da Cruz et al. (2020)	Conference Article	International Conference on Enterprise Information Systems (ICEIS)	Prototype	Agnostic	Organizations and Their Supply Chains
22	Sadawi et al. (2021)	Journal Article	Technological Forecasting and Social Change	Literature Review	Agnostic	Markets
23	Schletz et al. (2020)	Journal Article	Sustainability	Framework	Agnostic	Markets
24	Schletz et al. (2022)	Journal Article	Frontiers in Blockchain	Framework	Agnostic	Markets
25	Schletz et al. (2023)	Journal Article	Frontiers in Blockchain	Framework	Agnostic	Markets
26	Shou and Domenech (2022)	Journal Article	Journal of Cleaner Production	Single Case Study	Textile	Organizations and Their Supply Chains
27	Tang et al. (2018)	Journal Article	Climate Policy	Policy Recommendations	Agnostic	Markets
28	Tóth et al. (2021)	Journal Article	Energies	Multiple Case Study	Automotive	Organizations and Their Supply Chains
29	Wang et al. (2020)	Journal Article	Sustainability	Literature Review	Agnostic	Organizations and Their Supply Chains
30	Woo et al. (2021)	Journal Article	Building and Environment	Literature Review	Building	Organizations and Their Supply Chains
31	Woo et al. (2020)	Conference Article	Conference on Blockchain Research & Applications for Innovative Networks and Services (BRAINS)	Framework	Building	Markets
32	Yan et al. (2022)	Journal Article	Buildings	Literature Review	Building	Organizations and Their Supply Chains
33	Zampou et al. (2022)	Journal Article	Journal of the Association for Information Systems	Design Science Research	Agnostic	Organizations and Their Supply Chains
34	Zhang et al. (2020)	Journal Article	Resources, Conservation and Recycling	Framework	Agnostic	Organizations and Their Supply Chains
35	Zhang et al. (2022)	Journal Article	Journal of Sensors	Simulation Experiment	Logistics	Organizations and Their Supply Chains

is reached (i.e., no new concepts, properties, or interesting links arise) (Wolfswinkel et al., 2013).

Results

The following section outlines our results in the form of a comprehensive framework for scholars, industry experts, and policymakers to effectively design, evaluate, and further develop approaches for data sharing in CA to enable automated and sustainable supply chain management (cf. Figure 2). On that basis, we elaborate on the role of digital technologies in supporting automated data sharing in supply chains for CA.

Based on our SLR (cf. Appendix A), we identify four main categories for automated data sharing that need to be considered and addressed by organizations to assess CA practices in supply chains: *data quality*, *integration and interoperability*, *data flows*, and *data governance*. We find that integration and interoperability as well as data flows are the two categories that enable automated data sharing from an implementation point of view, as only interoperable or integrated systems with end-to-end data flows can facilitate data sharing in supply chains without or with reduced human intervention (i.e., automated) (Xu et al., 2024). Further, we find that data quality and data governance both address the functional requirements for the usage of data in an automated system. High quality throughout the data life cycle, even across organizational boundaries, ensures the exchange of useful data. A robust governance framework should aim to facilitate the (data) sovereignty of stakeholders to establish trust between them and thus foster their willingness to share data along supply chains (Nitsche et al., 2021). Specifically, while our categories integration and interoperability and data flows ensure that data *can be shared automatically*, the category data quality determines whether the *shared data are useful*, whereas the category data governance defines the *sovereignty over the shared data*. While these categories serve different purposes (i.e., usefulness, automation, and sovereignty), they are equally essential for achieving *meaningful data sharing* in the context of CA and, consequently, supply chain automation. This is reflected in the balanced distribution of publications contributing to each category in our SLR (cf. Appendix A). Consequently, we formulate our results accordingly (i.e., our categories are illustrated in parallel with no particular order or hierarchy in Fig. 2).

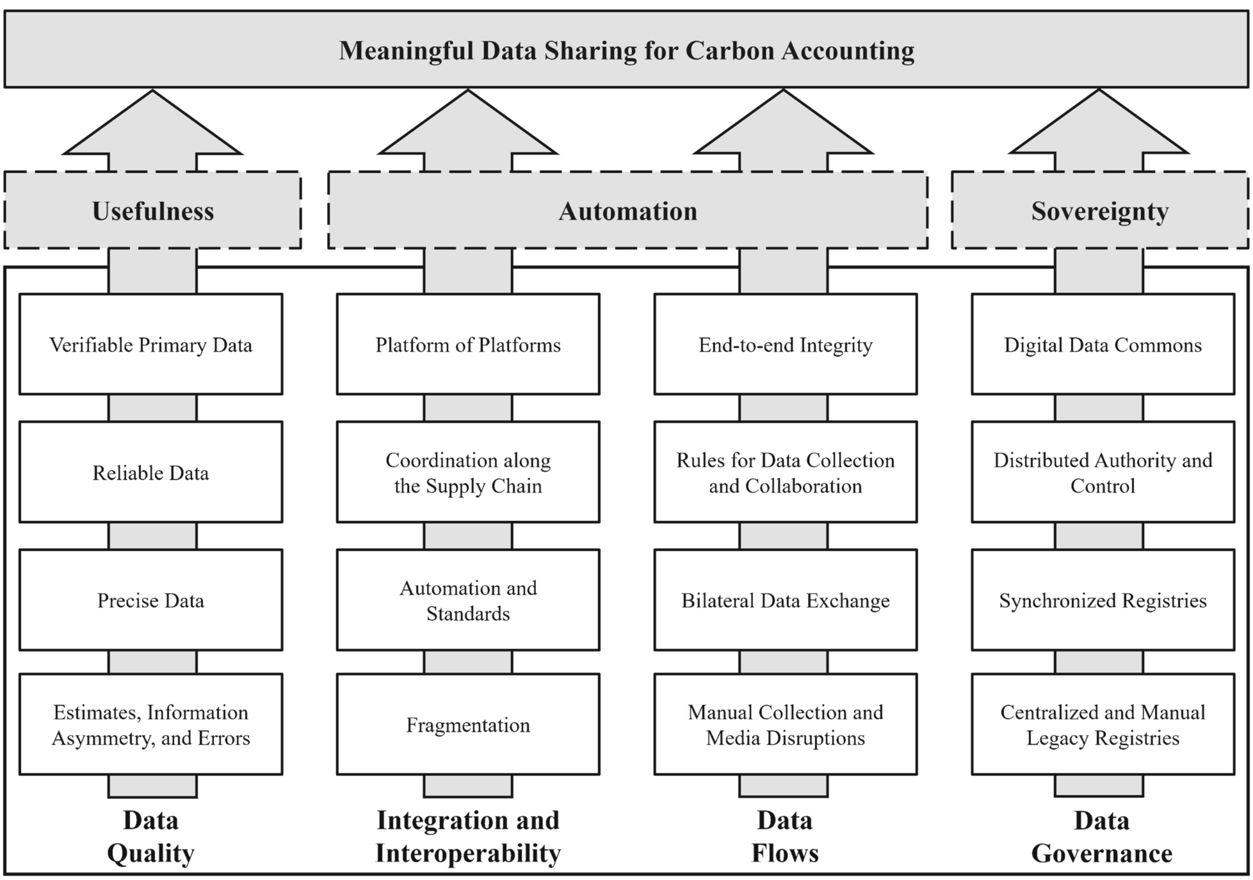

Fig. 2 Framework for meaningful data sharing in supply chains to support CA within and beyond organizations' boundaries

Through iterative axial coding, we identify four sub-categories within each main category. We sort these sub-categories ascending according to the level of digitalization: From manual processes, to the use of legacy systems, to the integration of emerging digital concepts, and technologies to enable meaningful data sharing for CA (cf. Table 1). By doing so, our framework allows organizations to assess their current level of digitalization and identify steps toward enabling automated inter-organizational data sharing. Below, we describe the categories and their relations in detail, highlighting how digital technologies underpin and shape each category.

Data quality

Our framework's first main category is data quality. High-quality data can be defined as data that is fit for use by data consumers (Strong et al., 1997). Following this definition, data quality can be categorized in intrinsic (e.g., accuracy), accessibility (e.g., access security), contextual (e.g., completeness), and representational (e.g., consistent representation) data quality (Strong et al., 1997). Ensuring a high data quality related to GHG emissions is often difficult due to the fact that most IS used in supply chain management, such as ERP or routing systems, generally do not include emissions data (Zampou et al., 2022).

Our first sub-category is *estimates, information asymmetry, and errors*. As illustrated above, in legacy systems, MRV is mostly performed manually, thereby often not achieving high consistency, rigor, accuracy, and completeness (Lorenzo-Sáez et al., 2022; Schletz et al., 2020; Yan et al., 2022). The result can be errors (e.g., double counting), fraud, a lack of traceability to source, difficulties in extraction and analysis of data, long confirmation periods, (costly) administrative work, and a lack of incentives to reduce emissions (Ju et al., 2022; Li et al., 2023; Mandaroux et al., 2021; Tang et al., 2018). These issues in legacy accounting systems can also hinder sectors and industries from participating in carbon markets (Woo et al., 2021). Especially verification is often a manual expert process, and in some areas, there is a lack of verifiers with expertise (e.g., in accounting for methane emissions) (Olczak et al., 2022; Schletz et al., 2023). In summary, MRV data in legacy systems are often not reliable, especially when they require multiple inputs and outputs at different stages of the supply chain (Shou and Domenech, 2022; Tóth et al., 2021; Zhang et al., 2020). Regarding explicit CA methods that are currently widespread, production-side CA relies heavily on carbon emission factors and energy statistics (Liu et al., 2022). Production-side CA also faces difficulties in supporting more fine-granular carbon emissions research due to the long time lag in the release of energy statistics, which are generally only available at an annual scale. Consumer-side CA has the benefits of a less complex calculation and a widespread adoption (Liu et al., 2022). In the building sector, for example, carbon data are typically based on consumption and emissions modeling instead of empirical data collection (Woo et al., 2020). There is, however, a time lag in collecting product activity data and releasing respective tables, and temporal as well as spatial resolution are typically low (Liu et al., 2022).

Recent literature illustrates the importance of digital and automated data collection, particularly regarding MRV, to enable a more *precise data* (Körner et al., 2023; Müller et al., 2023; Zampou et al., 2022). Liu et al. (2022), for example, outline a technical system that can be used for near real-time calculation of global carbon emissions based on sectoral activity data, thereby addressing the granularity challenges of current systems. The use of such a system can, depending on the implementation, be very costly and time-consuming (Liu et al., 2022). Against this background, Schletz et al. (2023) point out that combining remote sensing and deep learning may significantly enhance accuracy and scalability. Wang et al. (2020) similarly suggest using automatic sensors to efficiently improve integrity and accuracy. For specific use cases like monitoring gas streams, there are already implemented practices for efficient and precise monitoring like continuous emission monitoring systems, which, e.g., Li et al. (2023) adopt, using a carbon emission meter certified by an environmental protection department. For other use cases (e.g., in infrastructure in buildings), scholars propose leveraging digital twins and the Internet of Things (IoT) (Yan et al., 2022).

Our third sub-category is *reliable data*. Blockchain technology and tokenization are often proposed to provide reliable information and avoid double counting (e.g., in monitoring, tracking, and reporting of carbon emissions and trading transactions) (Diniz et al., 2021; Franke et al., 2020; Muzumdar et al., 2022; Sadawi et al., 2021; Wang et al., 2020). By using a blockchain system that ensures records are kept unchanged, manipulation can be prevented (Ju et al., 2022). Schletz et al. (2020) additionally point to the use of smart contracts to automate enforcing MRV procedures, thereby reducing costs for data collection and improving data quality. As an approach to solving the problem of how to ensure that the real-world data entering the system is trustworthy (i.e., the oracle problem) for CA in the electricity sector, Babel et al. (2022) propose using smart meters, devices that can record and transmit accurate electricity data in real-time, enabling the calculation of corresponding carbon footprints. These smart meters would receive a unique and non-transferable digital identity from a trusted third party during installation, where the public keys are stored in a registry. In this context, Li and Li (2021) argue that trusted identity certificates can be issued on a blockchain network. In such a decentralized network, a smart contract could bind the user's identity to their public key, which not only enhances the trustworthiness of user identities, but also increases the efficiency and transparency of the identity verification process.

Our final sub-category related to data quality is *verifiable primary data*. Verifiable primary data refers to data collected directly, such as through measurement with sensors, which can be independently verified. Various researchers have proposed blockchain-based approaches for CA or carbon trading to achieve verifiability through cryptography (e.g., Chakraborty et al., 2022; Ju et al., 2022, or Sadawi et al., 2021). Sharing verifiable primary data can not only ensure a high data accuracy and authenticity, but also allows data sharing without a reduction of quality along the supply chain through the aggregation for different data formats. For instance, Babel et al. (2022) illustrate on the example of the electricity sector how verifiable primary data can be traced back along the supply chain to an individual power plant, thereby allowing end consumers to receive trustworthy and precise data about their emissions.

Integration and interoperability

The second main category of our derived framework is integration and interoperability (Babel et al., 2022; Guzman et al., 2019; Mandaroux et al., 2021; Schletz et al., 2022)). Kim and Baumann (2022) emphasize that the dissemination of standards and methodologies is a key issue in climate change mitigation. According to them, a digital MRV system must provide enough flexibility to accommodate this dissemination and allow for adequate interoperability between systems using similar classes of methodologies and standards. The integration of CA into climate policies, IS, and markets is crucial for establishing a digital carbon management (Körner et al., 2023). Achieving this integration requires interoperability among all actors and their respective systems, facilitating the consideration of data sources to ensure accountability for all actors (Schletz et al., 2022). Therefore, scholars emphasize the importance of CA architectures that are interoperable with existing infrastructure (Mandaroux et al., 2021; Schletz et al., 2022).

Our first sub-category is *fragmentation*. It is characterized by data silos and very heterogeneous data formats (Guzman et al., 2019; Ju et al., 2022; Li et al., 2023). Data silos result in isolated pools of information (even within organizations), obstructing seamless communication and collaboration. Heterogeneous data formats increase the complexity of IS and pose interoperability challenges, hindering efficient data analysis and integration across diverse systems. Current CA solutions incorporated in organizations' ERP systems are often fragmented and therefore lack interoperability and end-to-end verifiability (Babel et al., 2022). Existing barcode and RFID tracking systems also typically represent fragmented solutions with limited purposes and fixed data structures (Wang et al., 2020).

Our second sub-category, *automation and standards*, describes digital CA approaches in which most internal processes (i.e., intra-organizational) are digitized and automated, often due to efficiency improvements (Tang et al., 2018; Tóth et al., 2021; Zhang et al., 2020). This sub-category is characterized by an integration of digital technologies into the CA processes. For infrastructure and buildings, Yan et al. (2022), for example, argue for the necessity of adaption and integration of building information modeling in CA tools to provide a digital environment that clarifies the complexity of assets' elements and system boundaries and achieving a higher degree of automation. For transportation, Ajufo and Bekaroo (2021) present an application that automates the calculation of carbon footprints of individuals by using location tagging, GPS, and built-in algorithms by autonomously detecting parameters such as distance traveled and mode of transport used, thus eliminating manual user input. Standardization makes different data sets comparable. This is essential for aggregation (Schletz et al., 2023). Universal standards can provide the basis for the interoperation of digital CA systems with other CA systems or legacy systems (Mandaroux et al., 2021). Against this background, Tang et al. (2018), for example, argue for standard file specifications: They propose an integrated system that covers the entire compliance cycle, including, among others, monitoring plans, emissions reports, and multi-stakeholder access. Lorenzo-Sáez et al. (2022) build a sectoral and territorial information system for GHG emissions monitoring based on the standardization of the Intergovernmental Panel on Climate Change (IPCC) to ensure interoperability and coherence with other quantification methods and systems. Regarding automation and standards, organizations can take multiple measures, such as implementing sensors or visual scanners with IoT solutions to collect and share GHG data, recording standardized units, automating calculations for key metrics, and automating data entry for reports (Ito et al., 2022; Zhang et al., 2022).

Coordination along the supply chain is characterized by industry-specific standards for data sharing (Schletz et al., 2022). Compared to more isolated approaches, this allows for enhanced transparency, efficiency, and interoperability throughout organizations' supply chains. In the infrastructure sector, Yan et al. (2022), for example, point out that building information modeling adaption enables data sharing, e.g., for Life Cycle Assessments (LCAs), thereby facilitating technical interoperability. A combination of digital technologies can be used and should work in conjunction to enable coordination along the supply chain. In particular, various IS researchers explore the use of blockchain in combination with other digital technologies, such as AI, big data analytics, or IoT (e.g., Körner et al., 2023, Franke et al., 2020, or Wang et al., 2020). Sadawi et al. (2021) propose an approach in which sensors are directly connected to a blockchain). With this approach, they aim to solve the vulnerability to privacy and security threats of using wireless sensor network technology as an operating platform for IoT devices by integrating blockchain (Sadawi et al., 2021). Similarly, Chakraborty et al. (2022) and Woo et al. (2021) suggest sharing measurement data from sensors or smart meters directly using blockchain technology for CA and trading applications. This technology secures the verification of data through a decentralized network of nodes, where each transaction is permanently recorded on a tamper-proof ledger after validation by the nodes. Smart contracts (i.e., self-executing programs) can improve the degree of automation of blockchain-based approaches. Sadawi et al. (2021), for example, suggest using them to calculate carbon budgets without human intervention. This can ensure highly secure, replicable, and auditable transactions (Schletz et al., 2023). "Smart standards," designed and harmonized using information technology into ontologies of quantification methodologies and verification standards, can additionally enable the development of smart contracts executable on, and interoperable between, different blockchains. Providing the necessary standardization, interoperability, and exchangeability is the role of Semantic Web ontologies in this regard (Kim and Baumann, 2022).

A *platform of platforms* is achieved when recorded carbon data is reachable and referenceable in a semantically comparable manner. A "nested" accounting system can enable the collection and aggregation of data from different actors using IoT devices, thereby automating the collection and processing of data from different sources (e.g., through a platform hub) (Schletz et al., 2020, 2022). Given privacy concerns, digital approaches, e.g., based on ZKPs, can provide anonymization while allowing traceability and cryptographic verifiability instead of full transparency (i.e., disclosure of all data). Also, Sadawi et al. (2021) point out that there may not be one single blockchain that covers all use cases, but rather multiple chains that work together.

Data flows

To enable inter-organizational data sharing, many digital CA approaches leverage IS to improve data flows between supply chain partners (Babel et al., 2022; Heiss et al., 2023; Zampou et al., 2022). Our corresponding sub-categories for data flows are manual collection and media disruptions, bilateral data exchange, rules for data collection and collaboration, and end-to-end integrity.

In legacy systems, MRV is typically characterized by *manual collection and media disruptions* performed manually based on disconnected data trails, static reports, and spreadsheets (Schletz et al., 2020). This complicates tracing data back to the source and therefore leads to a lack of transparency and information asymmetry in applications that rely on these data, e.g., carbon markets (Sadawi et al., 2021; Franke et al., 2020; Tang et al., 2018).

Our framework's second sub-category is *bilateral data exchange*. According to Yan et al. (2022), the evolving need for multi-stakeholder collaboration and access to cloud services and web-based applications is driving the use of advanced digital technologies instead of relying on spreadsheets and stand-alone software. Current collaboration is, however, often difficult due to data confidentiality concerns and a general lack of trust. Organizations are often cautious about sharing carbon data, for example, because of concerns that suppliers might use this environmental information in the selection process or because of fears that revealing sustainability performance that is inferior to competitors could damage their reputation (Olczak et al., 2022; Zampou et al., 2022). As a result, organizations currently often only share their data bilaterally, rooted in established trust and specific collaboration agreements. For example, organizations may opt to share carbon data exclusively with direct suppliers, with whom they have established long-term business relationships, thus limiting a necessarily comprehensive data flow across the entire supply chain.

Standardization of the *rules for data collection and collaboration* can facilitate the sharing of carbon data along supply chains (Zampou et al., 2022). Establishing collaboration rules can be challenging, among others, due to the sensitivity of carbon data (Müller et al., 2023). This illustrates the need for privacy concerning users and their shared carbon data to enable collaboration and data sharing Franke et al. (2020). One technology often proposed is blockchain, which aims to ensure a more reliable flow of data, address supply chain disruptions, increase transparency, and reduce information asymmetry (Franke et al., 2020; Wang et al., 2020). For example, da Cruz et al. (2020) propose a smart contract-based platform for tracing the carbon footprint of products and organizations, using the blockchain for registering and sharing data between organizations and end-consumers. Shou and Domenech (2022) as well as Zhang et al. (2020), similarly, propose blockchain-based frameworks aiming to enhance traceability and data sharing.

Our last sub-category is *end-to-end integrity* and emphasizes maintaining the integrity of data as it is transmitted across various sources throughout the supply chain, even when information is selectively shared (Heiss et al., 2023). To prevent manipulation, an end-to-end system should provide security, authenticity, and privacy regarding data storage and transaction transmission (Sadawi et al., 2021). Against this background, Babel et al. (2022) provide a concept for an end-to-end carbon tracking system that enables end-consumers to verify emissions data. This system uses a combination of emerging digital technologies, including fractional, non-fungible tokens for fine-granularity of the information, and employs PETs, specifically ZKPs, to address privacy issues. ZKPs allow to prove statements without disclosing additional information. In blockchain applications, they enable network participants to perform computations off-chain and then record only the results and a proof of correctness on-chain, effectively addressing the scalability and privacy issues commonly associated with this technology (Babel et al., 2022; Franke et al., 2020; Ju et al., 2022). Furthermore, ZKPs enable trustworthy pre-processing, which ensures that data from initial sources, such as sensors, is accurately processed before it is shared further, thereby significantly enhancing the integrity of the data source (Heiss et al., 2023).

Data governance

This category in our framework includes data sovereignty of individual stakeholders and addresses the distribution of decision-making power related to the sharing and utilization of carbon data. Distributing decision-making power is crucial for ensuring effective control over processes and data and necessary to facilitate broad participation, a fundamental goal of the Paris Agreement (Schletz et al., 2020). Therefore, data governance in the context of our framework should — while also respecting aspects such as authority and inclusivity — aim to achieve data sovereignty, enabling actors to maintain control over their data while contributing to the system, in alignment with the Agreement's emphasis on collaborative and decentralized climate action (Franke et al., 2020).

Existing CA systems are typically characterized by *centralized and manual legacy registries*, where decision-making power may be concentrated by entities, as exemplified by the United Nations Framework on Climate Change (UNFCCC) (Schletz et al., 2020). Such centralized structures introduce vulnerabilities, notably becoming potential single points of failure that can severely impede efficiency and scalability (Schletz et al., 2020). Also, a centralized system raises concerns about data availability and security, as the control over the data is handed to one or few organizations (Babel et al., 2022). One of the primary challenges in these systems is the difficulty of synchronizing different registries, which further exemplifies the tension between centralized governance and the principle of national sovereignty, particularly evident in the implementation of the Clean Development Mechanism (CDM) under the Kyoto Protocol (Schletz et al., 2023). Additionally, Franke et al. (2020) argue that the reliance on centralized registries leads to high transaction costs, primarily due to bottlenecks in permitting and bureaucratic processes, thus highlighting significant inefficiency in the governance of existing data sharing practices in current CA mechanisms.

Our second sub-category, *synchronized registries*, addresses the challenges posed by isolated registries through the integration and interconnection of these systems. In this context, several publications argue for the need for a unified platform as meta-registry (Diniz et al., 2021; Franke et al., 2020; Schletz et al., 2020, 2022). One approach, exemplified by initiatives such as the World Bank's Climate Warehouse, aims to link national registries and enable integrity and environmental transparency on a single platform (Schletz et al., 2020). However, the lack of interoperability due to the vast heterogeneity of different registries poses the same substantial barriers to integration as in the context of the organizations discussed earlier (Schletz et al., 2020). Several authors mention blockchain-based approaches as a suitable solution for aggregating different emission systems into a unified platform (Diniz et al., 2021; Schletz et al., 2020). Blockchain can establish trust through decentralized data storage and governance, facilitated by the collective participation of nodes within the network. This ensures that all parties have the ability to contribute and audit, reinforcing the Agreement's emphasis on empowering individual actors to actively take part in global climate action efforts without central registries as intermediaries, as the UNFCCC Executive Secretary's recognition of blockchain's potential to integrate stakeholders more effectively and create global public goods illustrates (Franke et al., 2020; Kim and Baumann, 2022). However, the architectural design of the blockchain network plays a crucial role in determining its efficacy. Merely migrating to a blockchain-based data storage infrastructure (e.g., by simply bridging disparate data silos with a blockchain network) could potentially increase the fragmentation (Babel et al., 2022). Moreover, depending on the architecture of the network, a unified platform could inadvertently centralize control with the owner of the blockchain network, thereby inheriting the problems of centralized and isolated registries we describe above (Babel et al., 2022; Schletz et al., 2023; Wang et al., 2020).

Our third sub-category is *distributed authority and control*. Franke et al. (2020) argue that blockchain technology embodies the democratic principles of the Paris Agreement by fostering decentralized governance. Regarding concrete blockchain architectures, several authors advocate for a permissionless blockchain for participation and auditing, where anyone can participate without requiring a third party (e.g., Schletz et al., 2023 or Wang et al., 2020). In contrast, Mandaroux et al. (2021), propose a permissioned blockchain where only known and trusted institutions can participate as the underlying infrastructure, as this approach reduces overhead and thus provides the necessary transactional efficiency. In addition, smart contracts are repeatedly discussed as a key component, offering enhanced transparency and trust by automating the enforcement of rules and audits. This promises to significantly streamline administrative processes, as opposed to the inefficiencies inherent in centralized and manual legacy systems (Franke et al., 2020).

The transition to a *digital data commons* involves decentralizing both governance and data storage, marking a significant shift toward more inclusive and sovereign data sharing practices. This paradigm shift aims to provide all participants with access to accurate, high-quality data while ensuring their individual data sovereignty (Franke et al., 2020; Ito et al., 2022). This decentralized and verifiable data can be used to enable digital MRV processes that increase trust and support the development of new and innovative financing and governance models (Schletz et al., 2023). In this context, Mandaroux et al. (2021) highlight the importance of SSI for strengthening individual data sovereignty within the digital data commons. By enabling participants to manage their identities and data through decentralized identity standards, SSI can not only increase their control over their personal data, but also broaden the applicability of data sharing by including emissions data in verifiable credentials.

Discussion

In this section, we discuss the results of our research and draw on its implications. Based on our findings as well as the scholarly discourse that we analyzed in our SLR, we identify two transformative developments that organizations experience in the context of digital CA as they integrate digital concepts and technologies (cf. Table 1) and move upward along the sub-categories of our framework: First, we observe a development toward a synergistic integration of digital and sustainable transformation, often referred to as twin transformation, where sustainability data is utilized for multiple purposes. Second, we identify development from an intra-organizational approach to an ecosystem perspective of CA, encompassing the use of accurate (primary) data across and along supply chains. As illustrated in Fig. 3, these developments can lead to supply chain automation and efficient markets through meaningful data sharing, including but not limited to CA. In this section, we present these two developments and their implications, while also providing an outlook on future research potential and real-world implementations.

Development 1: Development from separate digital and sustainable transformation toward twin transformation

The first noteworthy development against the background of our paper involves organizations moving from separately addressing issues related to sustainable and digital transformation toward a joint consideration of their digital and sustainability areas (i.e., twin transformation). This approach allows organizations, for example, to process environmental data from sensors through AI and identify patterns to enable sustainable decisions and simultaneously generate new data streams (Christmann et al., 2024). Aligning both transformative efforts can help organizations achieve their sustainability and digitalization goals and gain a competitive advantage. For example, this means that an advanced digital transformation is able to boost sustainability measures in organizations — and vice versa, an advanced sustainability transformation requires (and hence promotes) a high level of digitalization.

Our SLR reveals how this development within organizations toward twin transformation — with respect to carbon data — manifests in practice: While organizations initially focused on basic IT-based digitization of existing CA practices for efficiency or compliance reasons (Babel et al., 2022; Ju et al., 2022; Li et al., 2023), we now see a fundamental development toward leveraging digital transformation as an integral enabler for sustainability transformation of organizations and vice versa (Schletz et al., 2023). To provide a better understanding of how twin transformation is exemplified with CA, we describe below corresponding developments in the four key categories of our framework:

Data quality experiences a fundamental development away from reliance on averages and estimates toward real-time, granular data collection (Babel et al., 2022). Digital technologies to enhance carbon data collection (e.g., IoT sensors and smart metering devices) are increasingly deployed, not only to comply with regulations such as on non-financial reporting but also to gain competitive advantage (e.g., through enhanced risk management) (Müller et al., 2023; Tóth et al., 2021). Regarding *integration and interoperability*, organizations move from the collection of carbon data in silos (i.e., non-accessible for other departments or use cases)

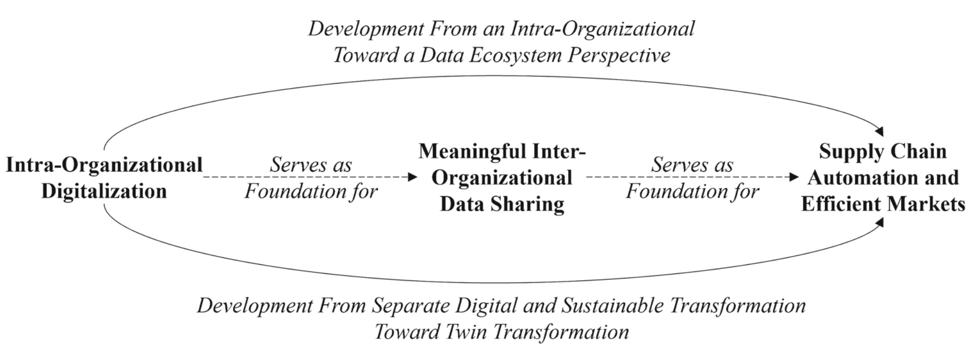

Fig. 3 Transformative developments from intra-organizational digitalization to supply chain automation and efficient markets

toward integrated, enterprise-wide systems for collecting, storing, and utilizing this data, for instance by establishing "centers of intelligence." This exemplifies the twin transformation by coordinating emissions data management and ensuring consistent standards, which allows using carbon data across stakeholders and systems (Müller et al., 2023). Similarly, *data flows* have evolved from a simple collection of carbon data to being enhanced through the strategic combination of digital technologies and concepts. For example, LCA software providers implement standardized data models that enable seamless interactions with other enterprise systems (Yan et al., 2022), allowing organizations to reuse collected carbon data for different purposes, such as compliance and strategic decisions. *Data governance* is evolving in this context as well, exemplified by a development toward domain-oriented architectures such as data meshes, which enable organizations to create value from their carbon data through decentralized ownership with domain expertise and by treating data as a product (Goedegebuure et al., 2024).

Ultimately, these individual observations within our framework's categories exemplify that the integration of digital technologies not only enhances carbon data management but also leads organizations to drive sustainability initiatives along with digitalization initiatives, thereby aiming to leverage twin transformation for strategic goals and long-term competitive advantage.

Development 2: From an intra-organizational toward a data ecosystem perspective

The second major development we see is characterized by organizations not only collecting (primary) carbon data about themselves and their direct activities (i.e., Scope 1 emissions data) but instead taking a broader ecosystem perspective focusing on collecting and sharing (primary) data along and across supply chains (i.e., Scope 2 and 3 emissions data), thereby significantly further developing their MRV processes: Traditional CA practices typically operate within organizational boundaries, limiting the view of carbon data to internal activities, and reliance on estimates or averages for other activities causing indirect emissions (cf. "Introduction" section). This traditional approach has started to develop, primarily driven by existing and anticipated regulations, such as the Corporate Sustainability Reporting Directive (CSRD), toward a view encompassing the whole supply chain. This development incorporates indirect emissions into intra-organizational CA, with efforts toward enhancing its accuracy and efficiency. Drawing on the example of MRV processes, this may include tokenization approaches based on DLT that aim to provide greater verifiability of carbon data along supply chains, thereby improving existing verification processes for indirect emissions (Kennelly et al., 2019; Zhang et al., 2020; Körner et al., 2023).

Our findings suggest a development toward an even more holistic, ecosystem-wide approach. This broader view not only encapsulates entire supply chains, but also integrates various organizations, sectors, and even countries. This (data) ecosystem perspective is exemplified by various data space projects, such as Gaia-X, and characterized by leveraging data as a strategic asset, rather than as a tool to mitigate unfavorable effects in supply chains (Ito et al., 2022; Möller et al., 2024). These data spaces aim, for example, to share carbon data in a transparent and verifiable way, while ensuring data sovereignty, thereby also significantly contributing to the further development of MRV processes. By doing so, they enable diverse applications of carbon data, such as reducing carbon leakage, identifying the most economically feasible carbon reduction opportunities, and promoting a societal change toward CO2-adaptive decision-making. This demands the involvement of stakeholders both inside and outside the supply chain, from suppliers to government agencies to technology providers.

Driven by regulatory requirements and the need for trusted cross-organizational decision-making, *data quality* is increasingly becoming an ecosystem-wide concern. Multiple research papers focusing on methods for collecting and sharing verifiable real-time (primary) data across organizations underline this development (e.g., Babel et al., 2022 or Heeß et al., 2024). As for *integration and interoperability*, organizations are moving from simply integrating carbon data into their internal systems (e.g., ERP systems) toward enabling broader interoperability with external stakeholders and markets, facilitating participation in carbon markets and inter-organizational collaboration (Schletz et al., 2023; Xu et al., 2024). *Data flows* are evolving from bilateral data exchanges toward ecosystem-wide networks where multiple organizations can share and leverage data collectively (Heiss et al., 2023). The automotive industry demonstrates this development with the Catena-X project, illustrating how carbon data can be shared and accessed by network participants in a data ecosystem. This ecosystem relies on the digital concept of data spaces, which standardize data sharing (e.g., related to carbon data for enhancing MRV processes) by providing technical specifications (e.g., data format and communication protocols) based on Gaia-X standards and frameworks (Möller et al., 2024). To establish rules, processes, and responsibilities related to data in such ecosystem-wide collaboration, *data governance* is developing toward federated models that balance individual data sovereignty with standardization and trust requirements (Möller et al., 2024). Here, especially SSI can provide the necessary foundation for secure authentication and authorization.

As exemplified by these observations across our categories, this development toward an ecosystem perspective in CA not only enhances the accuracy of carbon data but also fosters collaborative efforts among diverse stakeholders, enabling more effective and sustainable decision-making along and across entire supply chains.

Implication 1: Intra-organizational digitalization as a foundation for meaningful data sharing

The developments exemplify that organizations need a certain level of digitalization before they can effectively share data in an automated and meaningful way (e.g., for competitive advantage). In the literature we analyze, we observe different levels of digitalization across organizations: As stated above, some highly competitive industries, such as the automotive industry with Catena-X (Ito et al., 2022), have already started leveraging data ecosystems for automated data sharing, thereby requiring stakeholders within these industries to collect and share their data accordingly. These initiatives demonstrate that meaningful data sharing necessitates the coordinated implementation of complementary technologies and concepts, such as data spaces and SSI. This technical complexity underscores the importance of a holistic architectural approach rather than isolated technological solutions. Some stakeholders, such as small- and medium-sized companies, may still rely heavily on manual processes related to their (carbon) data management and, hence, cannot participate in such data-sharing practices. This can limit the usefulness of whole data ecosystems for these companies. Consequently, the heterogeneity in the level of digitalization within individual organizations directly affects whether or to what extend they can benefit from automated data sharing. Based on our framework, organizations can assess their current level of digitalization and identify necessary steps toward enabling automated data sharing.

Using our framework as a starting point, future research should conduct dedicated papers focusing on concrete questions related to the practical implementation of digital technologies from an intra-organizational point of view (i.e., from a data strategy and deployment perspective). For example, further research could include case studies examining organizations that currently implement digital technologies in this context and document their learnings, such as prioritization, and hindrances, such as technology acceptance issues. This would complement our theoretical framework with practical insights and could provide organizations with a sophisticated roadmap for implementation.

Implication 2: Meaningful data sharing as a foundation for supply chain automation and efficient markets

As the developments illustrate, organizations increasingly foster data sharing as it represents one major antecedent for supply chain automation (Nitsche et al., 2021; Xu et al., 2024). Supply chain automation can be beneficial for entire supply chains, as it can not only reduce the bullwhip effect (Chen et al., 2000), enhance resilience (Difrancesco et al., 2022), and improve supply chain collaboration (Leckel and Linnartz, 2023), but also provides the foundation for fostering sustainable practices in supply chains: As our example of carbon data illustrates, the automated sharing of sustainability data can enhance automated decision-making along and across supply chains in a way that it not only incorporates traditional metrics, such as costs, but also sustainability metrics, such as embodied emissions. While recent literature already points out the need for such decision-making for end-users and provides respective approaches to support behavioral change for individuals (e.g., Fuso Nerini et al., 2021), more research focusing on organizations and their supply chains is needed in this context (Krasikov and Legner, 2023).

By taking our framework as an orientation, organizations can achieve the necessary basis for intra- and inter-organizational data sharing and lay the foundation for establishing the necessary data infrastructure for data sharing, targeting automation in inter-organizational processes — thereby enabling both automated and sustainable supply chain management. Such supply chain management allows organizations to quickly adapt their processes, strategies, and business models based on sustainability metrics. A seamless integration of sustainability metrics into the decision-making process through automated data sharing not only promotes traceability along and across supply chains (Körner et al., 2024) but also enhances collaboration: Automated verification of information and execution of corresponding actions (e.g., purchasing if prices as well as emissions of a preliminary product are below a certain threshold based on smart contracts) can foster trust, especially with regard to sustainability claims (Heeß et al., 2024). This may facilitate business relationships and aid in driving collective efforts toward sustainability goals (Negri et al., 2021). Moreover, a data infrastructure that enables automated data sharing for sustainability metrics may be able to be expanded to incorporate other types of data as well, supporting other strategic or operative tasks. In this regard, the implementation of meaningful inter-organizational data-sharing practices for CA can serve as the foundation for fostering supply chain automation in other contexts.

This not only supports value co-creation (Ranjan and Read, 2016) (cf. "Background and related literature" section), but also reduces information asymmetries in supply chains and markets that currently exist due to the reluctance to share sustainability data along supply chains (Heeß et al., 2024; Preindl et al., 2020). Information asymmetries can lead to adverse selection ("lemons problem"), where market inefficiencies — and potentially even market failures — arise because consumers are unable to distinguish products of different quality due to a lack of information (Akerlof, 1978).

With regard to sustainability data, vendors could, for example, not be able to charge price premiums for low-carbon products as consumers cannot verify that claim, leading to a lack of incentives for sustainable production processes (as, e.g., illustrated by Heeß et al., 2024 for hydrogen). Supply chain automation through digital technologies can address these issues, and automated data sharing — if it is deployed in a meaningful way as highlighted in our study — facilitates such supply chain automation.

In this light, we encourage researchers at the intersection of IS and supply chain management to further integrate a data sharing perspective in electronic markets and to advance the automated sharing of (carbon) data in supply chains by applying an ecosystem perspective. Our paper represents a starting point for integrating these perspectives, providing valuable insights for inter-organizational data sharing with a focus on carbon accounting. In doing so, it lays a fruitful foundation for further research, as the application of digital technologies in this context may extend beyond carbon emissions to encompass other sustainability data.

Conclusion

The adoption of automated data sharing for CA within and beyond organizations' boundaries is imperative to comply with existing and upcoming regulations, to maintain competitiveness, and to foster sustainable practices for mitigating climate change. A robust CA system that enables such data sharing facilitates the quantification of emissions and helps to identify reduction potential and to reduce information asymmetries, thereby enabling, for example, the integration of CO2-adaptive decisions into automated supply chain management. Current approaches face several challenges, particularly in measuring inter-organizational, indirect emissions. Scholars have proposed a variety of approaches to address current CA challenges, but a holistic and guiding perspective on automated data sharing in supply chains to support CA within and beyond organizations' boundaries is still missing.

We provide such a framework not only for researchers but also to guide industry experts and policymakers through this complex field and to illustrate transition paths toward data sharing in supply chains to support CA. Our framework outlines four main categories — integration and interoperability, data flows, data governance, and data quality — each with four sub-categories. These categories systematize data sharing in CA and illustrate how digital technologies may be leveraged and work together to lay the foundation for automated data sharing. Our structured approach clarifies the technological contributions for data sharing to support CA and highlights the potential of these technologies to drive significant improvements in how carbon data is managed and utilized across the supply chain. By detailing the specific roles these technologies play within each sub-category, we provide a roadmap for integrating digital technologies into existing CA approaches to improve the accuracy and reliability of shared carbon data. A critical component of our framework is the emphasis on intra- and inter-organizational data sharing. The latter, in particular, is necessary to enable (automated) supply chain management decisions based on carbon data. Hence, our framework illustrates, in the case of CA, the first step toward sustainability-based automation of supply chain management, linking automated data sharing in supply chains with sustainable practices. Furthermore, based on our findings, we identify two developments: First, we see a development toward a synergistic use of the digital and sustainable transformation within organizations (i.e., twin transformation) that uses carbon data. Second, we notice a development from an intra-organizational toward an ecosystem perspective of CA that uses carbon data to enable a variety of use cases across and along supply chains. These developments underscore the critical role of integrating inter-organizational carbon data in automated supply chain management to enable efficient markets.

Of course, our research is also subject to several limitations. The paper's focus is mainly on how digital technologies can be used in order to improve automated data sharing in supply chains and we formulate our categories and sub-categories accordingly. We do not provide a perspective on, for example, regulatory changes that may have led to paradigm shifts or may influence CA in the future. Moreover, our grounded theory approach relies on academic literature, excluding insights from non-academic sources and practical implementations.

Given these limitations and adding to the research avenues outlined in the "Discussion" section, we advocate for future research to explore automated data sharing in supply chains to support CA from alternative vantage points, such as societal impacts, and to validate our findings through non-academic sources (e.g., by including gray literature or conducting expert interviews) to bridge the gap between theory and practice. In addition, we encourage scholars to focus not only on specific technologies and their potential application in CA practices, but also to consider how these technologies can be used in combination and integrated into existing IS and processes to provide the greatest positive impact. Finally, future research may address non-technical issues, such as a possible regulatory framework that facilitates the sharing of carbon data within organizations, their supply chains, and prospectively in data ecosystems.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12525-025-00779-7.

Acknowledgements We gratefully acknowledge the financial support of the project 'ID-Ideal' (Grant-Number: 01MN21001I) by the Federal Ministry for Economic Affairs and Climate Action (BMWK) and the project supervision by the project management organization DLR.

Funding Open Access funding enabled and organized by Projekt DEAL.

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