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How blockchain technology improves sustainable supply chain processes: a practical guide

Rita Maria Difrancesco[1] · **Purushottam Meena**[2] · **Gopal Kumar**[3]

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Abstract

Blockchain technology has rapidly grown in the last decade and supply chain management has started to emerge as one of its possible fields of application. Blockchain is estimated to have a transformative impact and potentially transform and disrupt supply chains. However, despite recognizing its enormous opportunity, there is still an incomplete, dispersed, and fragmented knowledge of blockchain applications beyond cryptocurrencies. Very few business people still deeply understand how blockchain works and how it can concretely benefit supply chains. This paper contributes to closing this gap, providing a holistic approach to analyzing blockchain technology's applications and benefits in supply chain management. This study aims to support academics and practitioners in adopting a holistic perspective and realizing the potential this technology can offer in different areas of the supply chain, its managerial impact, challenges, and limitations. A "closed-loop" value chain perspective is adopted to analyze the benefits at each core process of the supply chain, from sourcing to final customer and reverse logistics. This paper conducts qualitative research using case studies analysis based on secondary data. Further, it builds a theoretical framework for blockchain-enhanced supply chain performance based on the results of the qualitative research. Finally, the paper discusses the major drawbacks and barriers to blockchain implementation, which help managers evaluate its real net benefits.

Keywords Blockchain technology · Supply chain management · Gartner Supply Chain Top-25 · Case studies · Theoretical framework

1 Introduction

In June 2018, a salmonella outbreak affected pre-cut melons from several United States (US) retailers–including Costco, Kroger, Trader Joe's, Walmart, and Whole Foods. It took weeks for the US Food and Drug Administration to identify responsible suppliers and all the stores where the melon was sold. If blockchain technology had been used, they could have contained the outbreak and avoided destroying the entire inventory of a product for safety precautions (Selk 2018). It is just an illustrative example demonstrating blockchain technology's importance and potential in supply chain management. Blockchain technology is gaining increasing attention among researchers and practitioners, and more and more companies have recently started to develop studies to evaluate its possible benefits. The concept of blockchain technology was first introduced in 2008 in a whitepaper on bitcoin authored by Satoshi Nakamoto (who is still an unknown person-or people). Born initially with bitcoin and conceptualized to facilitate cryptocurrency transactions, only a few years later, experts realized that cryptocurrency was just one application of blockchain and started investigating other application areas.

More recently, supply chain management experts have begun to analyze the possible benefits of blockchain implementation in this complex area. Today's supply chains are more complex than ever due to their global nature (Difrancesco et al. 2021)

✉ Rita Maria Difrancesco
rdifrancesco@eada.edu

Purushottam Meena
meenap@cofc.edu

Gopal Kumar
gopalkumar@iimraipur.ac.in

[1] Eada Business School Barcelona, Carrer d´Aragó 204, 08011 Barcelona, Spain

[2] Department of Supply Chain and Information Management, School of Business, College of Charleston, Charleston, SC 29424, USA

[3] Operations Management, Indian Institute of Management Raipur, Raipur 493 661, India

and companies have to continuously evolve and rapidly adapt to the different customers' needs, which require fast, agile, and dynamic supply chains. All these factors make companies' survival even more challenging; therefore, efficiency, effectiveness, speed, and transparency in their supply chains are even more critical. Blockchain technology is becoming so attractive for supply chain management because it can achieve a high degree of trust, accuracy and transparency, and real-time tracking of products, data, owners, and actions taken at any stage. The key role of trust, traceability, and transparency in supply chains has been widely discussed in the literature (e.g., Heese 2007; Skilton and Robinson 2009; Buell et al. 2016), and it shows how these characteristics can significantly improve supply chain performance. However, in practice, there is still a significant lack of visibility and transparency in supply chains. For example, a recent survey conducted by Deloitte with over 400 Chief Procurement Officers (CPOs) reveals that only 18% of CPOs have formal visibility of the risks in their tier-1 suppliers, and only 15% have visibility beyond that (Deloitte 2021). Moreover, such a lack of visibility increases as we move away from the manufacturer (O'Marah et al. 2014). Lastly, the explosion of globalization, and the growing attention to sustainability, have intensified even more the urgency to create greater transparency across supply chain networks (Awaysheh and Klassen 2010; Earley 2013; Di Vaio and Varriale 2020).

Blockchain development grew by more than 6,000% in 2018, and a recent survey by SAP found that 92% of business leaders view blockchain as an opportunity, with its major applications in several areas, including supply chains (Myerson 2018). Blockchain is estimated to have a transformative impact across supply chains and has the potential to transform and disrupt supply chains (Gartner 2018). Moreover, due to the Covid-19 pandemic, companies have started to accelerate their investment in technologies: a recent Gartner survey showed that nearly 70% of companies accelerated their digital transformation during the pandemic (Gartner 2021), emphasizing the increasing need for resilient and agile supply chains to prevent and deal with disruptions (Dutta et al. 2020). Forecasts highlight global blockchain technology revenue to grow significantly, reaching approximately $39 billion by 2025 (Statista 2020). However, despite recognizing its huge opportunity, very few business people still deeply understand how it works and how it can be implemented. A study conducted on European and US companies shows that a high percentage of the participants (43%, which rises to 65% if focusing exclusively on supply chain companies) does not look into blockchain yet or observed its development from a distance (Niels and Moritz 2017). Therefore, supply chain leaders must understand how to implement blockchain technology and explore its potential benefits. Most of the earlier studies and applications of blockchain technology were related to bitcoin and the financial area. However, other fields, like supply chain management, still lack knowledge and tests to support the evolution and possible implementation of blockchain technology in this area (Dutta et al. 2020; Cheung et al. 2021; Lim et al. 2021).

This study aims to support academics and supply chain practitioners in adopting a holistic perspective while getting familiar with the fundamentals of blockchain technology. While most of the literature on blockchain applications in supply chain mainly focuses on the food, pharmaceutical, and transportation sectors, this paper offers a more comprehensive view, including other industries such as automotive, fashion, electronics, cosmetics, and consumer goods. This supports and guides managers also in other supply chain sectors. This study offers a guide to realizing blockchain's potential in different areas of supply chains, the managerial impacts, and the limitations, to evaluate whether and how blockchain can add value to a business and undertake concrete initiatives in this direction. Specifically, the primary objective of this paper is to investigate which supply chain processes and which performance dimensions are mostly affected by blockchain technology adoption under the triple-bottom-line approach of sustainability.

First, some basic concepts, characteristics, and properties of blockchain are introduced and explained to address the above research objective. After that, the paper presents major applications of blockchain, focusing on supply chain management. Following a value chain approach, qualitative research is conducted using case studies analysis based on secondary data. The qualitative analysis is organized by clustering the different processes of the supply chain (i.e., sourcing and manufacturing, inventory management, distribution and delivery, retail, customer experience, product returns, and reverse logistics). We further investigate how blockchain technology can be implemented in each process and which supply chain performance dimensions are affected. Additionally, based on qualitative research results, a theoretical framework is developed for blockchain-enhanced supply chain performance. The paper also discusses the major drawbacks and barriers to implementing blockchain to help managers better evaluate blockchain technology and its net benefits.

This paper is structured as follows: Section 2 introduces the theoretical background and contribution of the article. Section 3 discusses the methodology and data collection. Section 4 presents the case studies along with a framework of blockchain applications in supply chain management. Section 5 discusses the results, findings, and limitations of the study. Finally, Section 6 presents the study's conclusion and offers future directions.

2 Literature review and contribution

This section reviews erstwhile literature and presents the theoretical background. First, an overview of the major technical aspects of blockchain technology is provided. Second, we discuss how blockchain technology can be used across the supply chain processes and its impact on sustainable supply chain performance. This paper complements the use of traditional indicators (such as cost and quality) with contemporary supply chain performance indicators, encompassing sourcing, manufacturing, inventory, distribution, retailing, customer experience, and product returns, to provide a holistic perspective (Bhagwat and Sharma 2007; Gunasekaran et al. 2004; Cho et al. 2012; Golrizgashti 2014; Carter and Rogers 2008; Koberg and Longoni 2019; Kumar et al. 2021). How blockchain technology can improve supply chain performance across these indicators is discussed in detail in Section 4. Finally, the study's unique contributions are presented based on the critical review of the literature.

2.1 Fundamentals of blockchain technology

Blockchain is built as a distributed database that stores a ledger of transactions shared across participating parties. It uses its network to authenticate transactions, and once the record has been created and approved by the network, it is cryptographically secured and stored. Once this occurs, the element cannot be altered or deleted. In this way, it creates an immutable and verified database (Maxwell and Kashni 2018; Azzi et al. 2019). Two main characteristics of blockchains that contribute to their popularity and infinite possibilities of applications are: (i) "trust" and (ii) "decentralization" (Seebacher and Schüritz 2017; Verhoeven et al. 2018). A blockchain is made trustable through its transparency (i.e., shared and verified information provided without the need of a third-party regulator), integrity (because of the cryptography and peer verification of transactions), and immutability (i.e., once a transaction is approved and recorded, it cannot be altered).

Furthermore, a blockchain has a decentralized nature, which allows for a high level of privacy for its participants, high reliability (data are shared and stored throughout the network), and versatility (its participants can integrate their own programs) (Seebacher and Schüritz 2017). Although blockchain was initially created (and still mainly used) as a public system, it enlarged with the years also to private systems, so that today one can distinguish between "public" (permissionless) and "private" (permissioned) blockchains. The first allows all participants to add or validate new blocks; the second allows access only to some participants, which may be necessary when, for example, a business needs to limit access to the network (Jochumsen and Chaudhuri 2018). More recently, two-hybrid systems have been created: "semi-private" blockchains, run by a single company that grants access to any user who qualifies, and "consortium" or "federated blockchain", where a pre-selected set of nodes controls the consensus process.

2.2 Blockchain and supply chain management

So far, most blockchain interest has been strictly related to its financial implications. Applications of blockchain technology in supply chains are still at an early stage, which represents a limit to understanding its potential, applicability, and benefits (Dutta et al. 2020; Cheung et al. 2021; Lim et al. 2021). In the last decade, supply chains have become more digital than ever. This transformation has been amplified and fueled by globalization, natural disasters, unpredicted events, and the increasing request for sustainability (Kopyto et al. 2020). As a result, it is becoming strictly necessary for supply chains to increase visibility, integration, traceability, resilience, agility, and data security (Bumblauskas et al. 2020; Lim et al. 2021; Ada et al. 2021; Baharmand et al. 2021), besides more traditional characteristics such as efficiency, speed, and quality (Carlan et al. 2022; Zhou et al. 2022). Since blockchain technology allows the integration of all supply chain members into a single secure network while sharing data and information (Dutta et al. 2020), scholars and practitioners have recently started exploring blockchain applications in the supply chain field.

However, the attention posed to it and its understanding is still very limited (Dutta et al. 2020; Lim et al. 2021). On the one hand, there is clearly incomplete and fragmented knowledge of blockchain applications beyond finance and cryptocurrencies (Yli-Huumo et al. 2016; Risius and Spohrer 2017; Kopyto et al. 2020; Tandon et al. 2021). Conversely, an increasing need to expand blockchain applications in other related sectors as there is great unexplored potential (Tandon et al. 2021). Too many companies focus on proving the technology works rather than assessing the value blockchain can bring to them (Bailey 2018). Current literature on blockchain technology in the supply chain reveals a dispersed knowledge of the topic, and there is a need to adopt a holistic view (Chang et al. 2020; Tandon et al. 2020; van Hoek 2020; Paul et al. 2021). Researchers have only recently started investigating blockchain technology's possible applications, concrete benefits, and challenges in the supply chain, often following a case study approach. Table 1 reviews the major studies identified in the current literature.

For each relevant study in the literature, Table 1 highlights the journal source, research objectives, the supply chain processes explored in the study, the industry sector, and the research methodology used. It can be observed that most of the studies address the upstream part of the supply chain (mainly sourcing and manufacturing) and distribution to improve transparency, the safety of the products, and traceability throughout the supply chain. So far, very little attention has been given to the role of inventory management and customers (Perboli et al. 2018; Ada et al. 2021). Nonetheless, inventory is central to guaranteeing a smooth and efficient supply chain, improving on-time delivery and customer satisfaction (Lee et al. 1997; Cachon and Fisher

Table 1 Review of the major literature on applications of blockchain technology in supply chain

Author(s)	Journal	Objectives	Main features	Industry	Methodology
Ada et al. (2021)	Sustainability	Identify traceability issues in the automotive supply chain	Sourcing and Manufacturing; Inventory	Automotive	One use case and simulation
Azzi et al. (2019)	Computers & Industrial Engineering	Development of theory and practice to analyze the requirements for implementing blockchain in supply chains	Sourcing and Manufacturing; Distribution	Digital technology for supply chain solutions	Two use cases
Baharmand et al. (2021)	International Journal of Operations and Production Management	How blockchain can support trust and transparency in humanitarian supply chains	Distribution	Humanitarian supply chain	Focus group and one case study
Brookbanks and Parry (2022)	Supply Chain Management: An International Journal	How blockchain can improve trust between buyer and supplier	Distribution	Beverage	One case study
Bumblauskas et al. (2020)	International Journal of Information Management	Analysis of how blockchain can be implemented to move goods in a more accurate and transparent way through the supply chain	Sourcing and Manufacturing; Distribution; Customers	Food	One use case
Cao et al. (2022)	Blockchain: Research and Applications	Transform supply chain governance in the beef supply chain with the implementation of blockchain	Sourcing and Manufacturing; Distribution;	Food	One use case
Carlan et al. (2022)	European Transport Research Review	Analysis of the costs and benefits in the maritime supply chains due to blockchain use	Distribution	Transportation	Modeling and one case study
Casado-Vara et al. (2018)	Procedia Computer Science	Development of a new blockchain to store all transactions for the agriculture supply chain	Sourcing and Manufacturing; Distribution; Retail; Reverse Logistics	Food	Theory and one use case
Chang et al. (2020)	International Journal of Production Research	The first effort to holistically analyze the opportunities of blockchain in global supply chains	Sourcing and Manufacturing; Distribution; Customers; Reverse Logistics	Transportation, Food, Pharmaceutical, Electronic, Automotive	Collection of 11 use cases
Di Vaio and Varriale (2020)	International Journal of Information Management	Analyze the linkage between blockchain, operations management, and sustainability	Sourcing and Manufacturing	Aviation	One use case

Table 1 (continued)

Author(s)	Journal	Objectives	Main features	Industry	Methodology
Dutta et al. (2020)	Transportation Research Part E	Identify opportunities, impacts, and challenges of blockchain adoption in the supply chain	NA	Finance, Accounting, Technology, Manufacturing, Transportation, Automotive, Energy, Healthcare, Food, Aviation, Construction, Online retail, Education, Entertainment and tourism, Online advertising, Spacecraft, Governments, Postal services	Literature review
Helo and Shamsuzzoha (2020)	Robotics and Computer Integrated Manufacturing	Development of a system for tracking and tracing through the integration of RFID, IoT, and blockchain	Sourcing and Manufacturing; Distribution; Customers	Energy	Literature survey and one use case
Jovanovic et al. (2022)	Technological Forecasting & Social Change	Analysis of the most significant important elements of a blockchain-based platform ecosystem	Distribution	Transportation	One case study
Kaijun et al. (2018)	Future Generation Computer Systems	Development of a public blockchain for agriculture supply chains	NA	Agriculture	Modeling and simulation
Kittipanya-ngam and Tan 2020)	Production Planning & Control	Analyze the challenges and opportunities in Thailand's food industry when digitalizing the supply chains	Sourcing and Manufacturing; Distribution	Food	Three use cases
Kshetri (2018)	International Journal of Information Management	Impact of blockchain on supply chain performance	Sourcing and Manufacturing; Distribution; Retail	Transportation, Fishing, Online retail, Defense contracting, Pharmaceutical, Luxury products, Retail, Electronic, Supply chain consultancy (traceability)	Collection of 11 use cases
Kumar et al. (2020)	Decision Sciences	Review of the permissionless blockchain Hyperledger Fabric and analysis of the challenges for blockchain in the food supply chain	Sourcing and Manufacturing; Distribution; Retail	Food	One use case
Kurpjuweit et al. (2021)	Journal of Business Logistics	Analysis of the potential, benefits, and barriers of blockchain adoption in additive manufacturing	NA	Manufacturing	Interviews and Delphi survey

Table 1 (continued)

Author(s)	Journal	Objectives	Main features	Industry	Methodology
Liu et al. (2021)	Computers & Industrial Engineering	Improving transparency, security, and integration in the drug supply chain by using a blockchain platform	Sourcing and Manufacturing; Distribution; Customers	Pharmaceutical	One case study
Mandolla et al. (2019)	Computers in Industry	Development of a digital twin along an additive manufacturing process for an aircraft company using blockchain	Sourcing and Manufacturing	Aircraft	One use case
Natanelov et al. (2022)	Journal of Industrial Information Integration	Analysis of the benefits of blockchain and smart contracts adoption for supply chain finance in the beef supply chains	Sourcing and Manufacturing; Distribution	Food	Agents Events Data (AED) method
Paul et al. (2021)	Technological Forecasting & Social Change	Analyze the impact and benefit of blockchain in the tea supply chain	Sourcing and Manufacturing; Distribution	Beverage	Structural equation modeling
Perboli et al. (2018)	IEEE Access	Design a standard methodology for blockchain use cases beyond finance and analyze benefits and criticalities in a case study in the fresh food industry	Sourcing and Manufacturing; Inventory; Distribution; Customers	Food	One use case
Tönnissen and Teuteberg (2020)	International Journal of Information Management	Develop an explanatory model for the interaction of actors in a supply chain involving blockchain	Sourcing and Manufacturing; Distribution; Retail; Customers	Pharmaceutical, Transportation, Food, Animal product, Retail, Online retail, Luxury products	Collection of 10 use cases
van Hoek (2019)	International Journal of Operations & Production Management	Application of the Reyes et al. (2016) framework on RFID to blockchain in the supply chains	Sourcing and Manufacturing; Distribution; Customers	Logistics services, food and beverage, and retail	Focus group, survey, and three use cases
van Hoek (2020)	Supply Chain Management: An International Journal	Implementing blockchain in the supply chain into the design of actual pilot projects	Sourcing and Manufacturing; Distribution; Customers	Logistics services, Consumer products, Retail	Three use cases
Verhoeven et al. (2018)	Logistics	Analyze blockchain technology adoption in the identified use cases	Sourcing and Manufacturing; Distribution	Transportation, Farming manufacturer, Supply chain consultancy (traceability), Retail	Collection of 5 use cases

Table 1 (continued)

Author(s)	Journal	Objectives	Main features	Industry	Methodology
Wong et al. (2020)	International Journal of Information Management	Analyze the effects of blockchain on small-medium enterprises in Malaysia	NA	Several industry sectors, including Electrical and electronics, Chemical, Textile, Food, Rubber and plastic, Machinery and hardware	Survey questionnaires and Partial least squares structural equation modeling (PLS-SEM)
Zhou et al. (2022)	International Journal of Production Economics	Quality and economic benefits of implementing blockchain in the food industry	Sourcing and Manufacturing; Distribution, Retail	Food	Structural equation modeling

2000). Similarly, evidence from the literature (e.g., Christopher and Ryals 2014; Ishfaq et al. 2016; Bumblauskas et al. 2020; Tönnissen and Teuteberg, 2020; van Hoek 2020) reveals how the role of customers in supply chains is becoming increasingly central. Therefore, a deeper analysis of the downstream part of the supply chain is required. Lastly, it is also found that only a few studies include reverse logistics and sustainability aspects. Given the increasing relevance of sustainability within supply chains (Di Vaio and Varriale 2020; Ada et al. 2021; Kumar et al. 2021; Difrancesco et al. 2022), it is evident that this represents a significant gap that urges to be addressed.

Concerning the industry focus, it is observed that the food industry is one of the most common (Bumblauskas et al. 2020; Kittipanya-ngam and Tan 2020; Kumar et al. 2020; Natanelov et al. 2022; Zhou et al. 2022), followed by the pharmaceutical and transportation sectors. The reason is that these kinds of sectors are usually connected to studies related to blockchain and product safety, trust, and traceability, which represent one of the major applications of blockchain technology to supply chains so far.

We can conclude that the current literature lacks a holistic framework: often, the papers present isolated case studies; other times mainly focus on the technical characteristic of blockchain implementation in supply chains. This evidences the need for a broader focus on blockchain technology applications that encompass the entire supply chain and highlights the link between blockchain, supply chain processes, and related performance. Based on these gaps in the literature, this paper makes one of the first attempts to develop a framework that connects the technical characteristics of blockchain on the one hand, and the supply chain processes and supply chain performance, on the contrary. Further, we explicitly match the blockchain characteristics—transparency, integrity, immutability, privacy, reliability, and versatility with the supply chain processes and performance. This study also highlights the need to identify the impact, benefits, and critical aspects of blockchain implementation for all the supply chain processes from a broader point of view.

2.3 Research gaps and contributions

Our analysis reveals the presence of emerging–yet insufficient–attention posed to blockchain applications in the supply chain. We identified several isolated case studies, focusing either on the technical aspects of blockchain implementation or on mere descriptive aspects of the case study. Only a few works leverage the benefits, the challenges, and the managerial consequences deriving from blockchain technology adoption. More specifically, no clear understanding of blockchain applicability, impact, and benefits has been analyzed in the supply chain context so far (Verhoeven et al. 2018; Lim et al. 2021). Researchers highlight the lack of a generalized view (Chang et al. 2020) and an unclear understanding of the coordination aspects, impact, and performance of blockchain's application in supply chains (Tandon et al. 2020, 2021). There are indeed limited studies on blockchain performance, given the topic's novelty and the difficulty of implementing it (Hong and Hales 2020). However, such topics are key for supply chain management (Lim et al. 2021), and all this represents an important disincentive for companies even to consider adopting blockchain technology.

This paper contributes to closing this gap, providing a holistic approach to analyzing blockchain technology's application and benefits in supply chain management. Our contribution is twofold. First, this paper provides an overview of the possible applications of blockchain technology in supply chain management—and a clear and structured analysis of its benefits, adopting a holistic view starting from the analysis of existing case studies and pilot projects. This study aims to help practitioners and decision-makers better understand and make strategic decisions on the design and implementation of blockchain in their supply chains. To address how blockchain can benefit supply chains, this paper adopts a value chain perspective (Porter 1985), analyzing the benefits at each core process of the supply chain, from sourcing to the final customer. Furthermore, to address sustainability concerns and implications, the paper takes one step further and adopts a closed-loop structure for the supply chain. Figure 1 presents the six core-processes approach followed in the analysis.

Second, a theoretical framework is developed to identify (i) which processes of the supply chain are affected by which blockchain technical characteristics, (ii) which processes of the supply chain predominately enjoy which performance improvement due to blockchain implementation, and (iii) which blockchain technical characteristics impact which supply chain performance.

3 Methodology

This research aims to create a comprehensive understanding of blockchain technology in the supply chain. It also develops a theoretical framework for blockchain characteristics, applications, potential, and benefits for supply chains. In doing so, we adopted a practical perspective supported by a theoretical foundation that helps us identify the more relevant issues in this area. Our approach consists of three subsequent and complementary phases. First, a conceptual overview of the topic is developed to delineate a theoretical background and identify the relevant research and practical issues and the research gaps (as already presented in Section 2). Second, qualitative research is conducted using case studies analysis based on secondary data. Finally, a theoretical framework is built based on practice.

The case study approach is commonly used in literature for conducting qualitative research, especially exploring new phenomena (Tönnissen and Teuteberg, 2020), such as blockchain technology. One of the major advantages of the case study approach is that theory can be developed starting from practice (Yin 1994; Recker 2013; Kshetri 2018). We utilized multiple-case studies rather than a single-case study approach, representing a stronger base for theory building (Rowley 2002; Kshetri 2018). The literature suggests using around 6–10 case studies for theory building (Kshetri 2018; Tönnissen and Teuteberg 2020).

Figure 2 summarizes the major steps used in case study analysis. To select case studies, we base our analysis on the latest Gartner Supply Chain Top 25 companies list (Gartner 2021). Specifically, we analyzed 30 companies consisting of the top 25 of Gartner's list, as well as the 5 "Masters", which refer to those companies recognized with "sustained supply chain excellence" (Gartner 2021). The 2021 Gartner list is provided in the Appendix Table 3. Gartner is considered

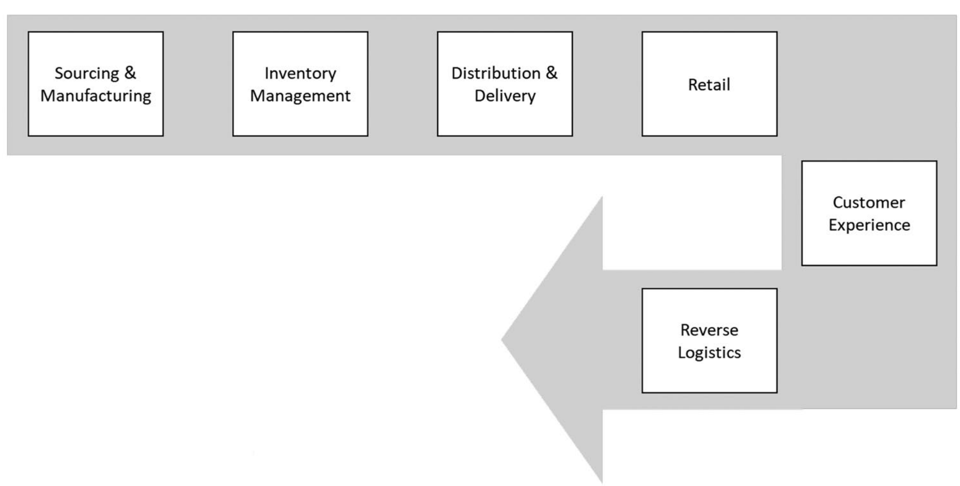

Fig. 1 The closed-loop value chain framework (adapted from Porter 1985)

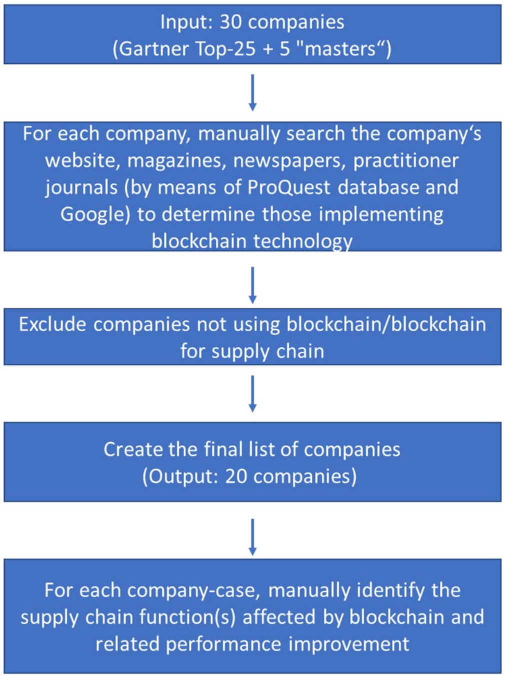

Fig. 2 Research methodology for the case study selection and analysis

a leading research and advisory company in supply chain management and technology; hence, we believe it can be accepted as a trusted, well-established, and well-recognized benchmark in academia and industry. It also assures the quality and the industry variety of the cases and that the case studies are of recent implementation.

To determine which of these 30 companies are implementing projects or pilot tests involving applications of blockchain technology in their supply chains, we manually searched the companies' websites, specialized magazines, newspapers, and practitioner journals (utilizing the ProQuest database and Google). Companies that are implementing blockchain projects not directly related to supply chains (e.g., PepsiCo using Zilliqa's blockchain platform to run an advertising campaign through smart contracts; Ma 2020) and those companies for which we could not find any information about blockchain implementation are excluded from the analysis. Based on this selection criteria, 20 out of the initial 30 companies qualified for further analysis. After selecting the companies, the resulting cases are coded as follows. Blockchain applications for each company are classified based on Porter's value chain framework proposed in Section 2, identifying which part of the supply chain is tackled in the project and the potential consequences, benefits, and performance improvements deriving from it. To ensure the rigor of the analysis and unbiased results, two authors performed the search, case selection, and coding independently. In case of any inconsistency, the third author contributed to the final decision.

The major limitation of the methodology used in this research is that it is very time-consuming, as authors have to search companies' websites, magazines, newspapers, and journals manually. Although the authors did an exhaustive manual search of news, still some cases might have been missed. However, this approach produces effective and unbiased data for the analyses. Another advantage and uniqueness of the methodology adopted here is the aggregation of literature review and news/case articles to build the theoretical framework. Hardly any study exists that adopts such an approach. The following sections present and discuss the results of the analysis. Finally, building on these results, a theoretical framework is proposed matching blockchain technical characteristics with the performance at each stage of the supply chain.

4 A blockchain-enhanced supply chain performance framework

Currently, most studies and applications of blockchain are related to financial aspects and cryptocurrency or its technical feasibility (Kopyto et al. 2020; Tandon et al. 2021). However, in the last few years, experts have identified blockchain technology's great potential based on bitcoin and are extending its possible applications to other fields. This section presents and analyzes the case studies collected from the Gartner Supply Chain Top 25 companies (along with the 5 Masters) involving blockchain projects specifically addressing supply chain issues. These results are later used to develop the theoretical framework.

4.1 Benefits of blockchain technology across different processes of supply chains

This section provides an overview of the main applications of blockchain technology in supply chain management, underlying how it can help to deal with supply chain challenges, and discuss examples of its implementation. As explained in Section 2.2, results analyses are organized following the value chain perspective.

4.1.1 Sourcing and manufacturing

Traceability throughout the supply chain has become extremely critical in the last decade. Knowing the source of all parts, having information about products' quality and quantities, and pinpointing a supplier in the case of a defective product all play a significant role in a company's daily business and in an entire supply chain (Zhou et al. 2022). However, tracking parts or products from their origin in a conventional way is a very difficult, costly, and time-consuming process. Blockchain technology offers the possibility to gain all this information and guarantee its truthfulness, assuring that nobody can tamper it.

Everybody in the supply chain can access and track all the data concerning suppliers and products or components in real-time.

A recent experiment conducted by Walmart in collaboration with IBM shows that blockchain technology can help track a product from its origin in a matter of seconds. In December 2017, Frank Yiannas, Walmart's vice president of food safety and health, asked his employees to track a mango from its origin. It took six days, 18 h, and 26 min to get an answer. Then, they repeated the test, this time in collaboration with IBM. From the start of their journey at the farm, pallets of mangoes were tagged with numeric identifiers. Every time they crossed another checkpoint—from farm to broker to distributor to store—their status was signed and logged. With the use of blockchain technology, it took about two seconds to get the result (Hackett 2017). According to Frank Yiannas, after two years of preliminary tests, Walmart and its suppliers are now ready to use blockchain in the food business (Ruso 2018).

Similarly, McDonald's joined the China Animal Health and Food Safety Alliance (CAFA) in order to build a blockchain-based "farm-to-table" project to track its food supply chain in China (Sinclair 2020). Several scandals on food health safety, like baby milk containing lethal amounts of melamine or rice containing heavy metals (Staff 2016), have motivated China to increase the attention posed to food security, traceability, and animal health to avoid similar issues from happening again. A step forward in this direction was taken on May 2, 2018, when several car manufacturers accounting for over 70% of global vehicle production in terms of market share (including BMW, Ford, General Motors, and Renault), formed a consortium called MOBI—Mobility Open Blockchain Initiative. Its goal is to support the mobility industry in implementing blockchain solutions to improve transparency, trust, sustainability, reduced user costs, and the risk of fraud (Mobi 2021; Staff 2018).

Further, blockchain technology can help to curb forced labor, especially in manufacturing. An example comes from Coca-Cola, which is currently studying labor and land rights for its sugar supply chains to protect workers' rights at every step using blockchain technology (Gertrude 2018). In 2020, Nestle partnered for the first time with the Rainforest Alliance and, thanks to the IBM Food Trust blockchain technology, can trace the coffee back to the farmers (Nestle 2020). Customers will then be able to track all the information related to the coffee they buy, including the time of harvest and the roasting period. Nestle is also developing a project with OpenSC, a blockchain platform founded by WWF-Australia and the Boston Consulting Group Digital Ventures to guarantee transparency on the sustainability of palm oil and milk (Nestle 2019). More specifically, Nestle will be able to make responsible decisions supporting farmers and producers who respect environmentally sound practices and human rights.

Similarly, Starbucks recently partnered with Microsoft to develop a blockchain solution to increase trust and visibility across its coffee supply chain (Almeida 2020). Besides the positive effect on supply chain traceability and customers (see Section 4.1.5), a major benefit also concerns farmers–including the smallest, geographically dispersed farmers since they are offered the possibility to access information on their final market easily and quickly, understanding where their beans end up and in which market their products are mostly sold and requested. Blockchain technology can also support suppliers and small manufacturers and protect them, especially from big firms: it is pretty common for suppliers to be paid with delays, which causes them to struggle to get enough financial resources to anticipate the capital and carry on their business until the payment occurs. Blockchain is estimated to have a huge potential, among other industries, in the food supply chain due to the increasing need for transparency, stricter legal and health requirements, and higher consumers' consciousness.

Blockchain can also help detect and prevent fraud in the upstream supply chain. Motivated by the new requirement imposed by the US Drug Supply Chain Security Act (DSCSA), blockchain technology has entered the health industry to allow information sharing and drug serialization. Giant pharmaceutical companies like AbbVie joined the MediLedger Consortium on a blockchain project that provides tracking and transparency in the supply chain in a robust and completely secure environment. The major benefits for companies are verifying the authenticity of products, identifying and tracing back potential frauds, and improving quality and trust (Zhou et al. 2022). Pfizer has conducted a similar project (called "End-to-End In-Transit Visibility") in order to provide a single source of truth on its products to its stakeholders. A major problem in the pharmaceutical industry is the presence of counterfeit drugs, leading to thousands of deaths (according to the World Health Organization, 10% of drugs are counterfeit).

On the supply side, we can conclude that adopting blockchain technology can improve performance measures like costs, speed, social impacts (e.g., healthcare), risks (e.g., frauds), real-time coordination, and quality measures.

4.1.2 Inventory management

Inventory management has become increasingly complex due to the growth of stock-keeping units (SKU), multiple sourcing providers, uncertainty in delivery times, fluctuating consumer demand, delays and mistakes in the paperwork, and inaccurate or missing information. As a result, companies have seen their risk of stockout increasing and their service level downgrading, which is translated into an economic loss (e.g., emergency orders to backup suppliers, contract penalties, and potential loss of customers). To mitigate the consequences of these issues, companies tend to increase the number of units they keep in stock, with the risk of keeping excessive inventory (and therefore higher carrying costs) and, even worse, contributing to the bullwhip effect in the supply chain. Blockchain technology offers a radical, new way to approach inventory management based on the fact that no piece of inventory can exist in the same place twice. As soon as a product changes its ownership or status (e.g., from work in progress to finished goods), this information is immediately updated and made available for all the blockchain members. Similarly, all the information, purchase orders, receipts, documents, etc., are stored and shared in the same permanent ledger and shared among the participants.

Furthermore, with this technology, supply chain partners can enable the automatic execution of payments and orders. Once recorded, transactions cannot be deleted and can only be updated by those parties, verified by the system, who write valid transactions. This provides all the supply chain actors with an accurate and transparent end-to-end view of products' information, like their location, quantity, quality, and ownership. As a result, companies can improve their forecast and the traceability of parts, increase their operating efficiency, create new opportunities for just-in-time optimization, optimize inventory levels, provide higher service levels, lower warehousing costs, improve quality, and reduce errors (Zhou et al. 2022).

Nike piloted a blockchain project that helps its retailers track the vast amount of inventory stored at different places. The company developed a common language and streamlined communication on a common platform to instantaneously and accurately record any movement or change in product status (Das 2020). Another application example comes from the electronic industry, where original equipment manufacturers (OEM) find it very difficult to track products from their suppliers. While a traditional tracking system is bounded within a single organization, a blockchain system allows cross-company tracking from the supplier's production line to the OEM warehouse. This way, organizations can spot sudden disruptions or bottlenecks as they occur and detect anomalies or fraudulent activities (IBM 2017). For example, Lenovo is optimizing the inventory procurement process in its supply chain using blockchain. The process of managing orders and invoices was previously based on paper, generating errors and leading to data loss. With the help of blockchain, the entire process has been moved to a secure platform so that every authorized party can access accurate and trusted records. The results show a significant improvement in terms of visibility, transparency, efficiency, speed, and revenue growth while decreasing costs. Blockchain technology can help control and monitor all product requirements throughout the supply chain and revise expiration dates based on this information, making it possible to use resources that otherwise would go wasted.

4.1.3 Distribution and delivery

Today's consumers are increasing more and more their expectations, demanding the product they want "right here, right now". In the last decade, the situation has become even more critical due to the explosive growth of online commerce, adding the challenge of fast and cheap (if not free) deliveries, detailed and accurate real-time information about orders, a trusted environment for cross-border trade, and personalized services. One of the key challenges to a company's success is properly managing its distribution system. Transportation and shipping companies have recently shown an increasing interest in blockchain and its application to transportation because it can help track and monitor all kinds of shipments and transactions throughout the supply chain, speeding up the paperwork and guaranteeing trust.

Companies like Alibaba and Walmart are exploring how blockchain can benefit their logistics thanks to its high level of visibility, transparency, and safety of transactions. Alibaba has recently started collaborating with New Zealand Post and Fonterra to track customers' orders using blockchain. The aim is to increase transparency and consumer confidence in response to the significant fraud challenge. In the case of positive results, Alibaba will consider implementing the system in its online marketplace (Shaw 2018). Walmart is analyzing how blockchain can automate and speed up its deliveries using a drone with a blockchain identifier: as the drone approaches the delivery box, the box itself reads the identifier, and if the code is valid, it opens and accepts the package. It would trigger a notification to the consumer's mobile device. Furthermore, all information related to the delivery (like time, location, temperature, etc.) would be stored and verified throughout the supply chain (Staff 2018). Similarly, L'Oreal is currently testing two pilot projects using blockchain technology to increase transparency and streamline international shipments with all the necessary paperwork (Haywood Queen and Brune 2019).

Finally, blockchain can help identify and prevent fraud in logistics. In this context, the most critical processes are usually transportation and change of ownership because criminals can tamper or provide fake documentation to pick up goods or introduce counterfeit products. Intel has introduced the "Intel Connected Logistics Platform", which allows users to track their shipments and monitor the condition of their products, like temperature and stock information. This platform can be very useful for those companies shipping fragile products or products with particular temperature requirements. Since both parties can access real-time information about the shipped product, disputes between carriers and shippers can be drastically reduced (Aouad 2018).

4.1.4 Retail

As retailers struggle in a margin-squeezed environment to obtain more results with fewer resources, the potential for blockchain to reduce operating costs is very promising (Weldon et al. 2017). According to a recent survey conducted on 321 European and North-American retail organizations, blockchain adoption is expected to cut costs by more than 2.5% according to 82% of respondents, while 36% said they believe the savings will be greater than 5%; and much of these cost savings could result from automation (Weldon et al. 2017). Another critical issue for retailers is the ability to prove the authenticity of their products, which is especially true in the food industry, luxury brands, or artwork. We have largely discussed in Section 4.1.3 blockchain's capability to track items' provenance throughout the supply chain, allowing retailers to access all the information concerning products. It helps them prove the authenticity of the items they sell or supports them in containing a food outbreak. Recall the example of Walmart discussed in Section 4.1.1; the retailer was able to provide accurate and real-time information to its customer about the mangos sold in its retail store. Another application of blockchain technology for retailers concerns payment methodology and acceptancy of crypto-currency payments. Global companies, including Coca-Cola, Amazon, and Starbucks, have recently introduced bitcoin payments in some of their markets, either directly or indirectly, through bitcoin-paid vouchers and gift cards (Tayeb 2021). It allows faster, cheaper, and safer payments (Deloitte 2021).

Ultimately, blockchain can also contribute to sustainability, offering retailers a way to contribute to environmental projects. This is the case of Ben & Jerry's, Unilever's subsidiary ice cream brand that introduced a retail platform based on blockchain technology in collaboration with Poseidon to allow customers to rebalance their purchases' carbon footprint (Smith 2018; Poseidon Foundation 2021). Poseidon's solution was tested in the Ben & Jerry's Scoop Store in London's Soho district and was based on the energy-efficient Stellar blockchain. Traditionally, environmentally responsible companies buy carbon credits to offset the greenhouse gasses deriving from their operations. The outcome is employed in developing environmental projects, like planting new forests or building new wind farms. However, this can be possible only on a big scale, it has a high barrier to entry, and the whole process is not at all transparent for customers. As a result, Poseidon's platform is based on decomposing carbon credits into micro-transactions that can be associated with every scoop of ice cream. In this way, the whole process is visible and transparent, and people can see the direct impact of their action, both environmental and economic ("on a $3 cup of coffee the carbon offset would cost less than two cents"; Smith 2018). Although it appears pretty clear that blockchain technology will transform the retail industry, many retailers are still reluctant to engage in this activity. They prefer to wait for the technology to be consolidated and fully ready to be implemented. Instead, retailers should take action today to ensure they are not left behind by competitors, keeping in mind that early adopters will also influence the development of networks and their rules (Weldon et al. 2017).

4.1.5 Customers' experience

The implications of blockchain technology for customers are numerous. Because of traceability, customers can get all the information about the item they buy, whether their mobile phone involves child labor or conflict-free resources, verify if the organic food they are buying is really respecting all the necessary requirements, and so on. This results in increased trust towards retailers and suppliers and increases customers' perceived value. In recent years, some studies (e.g., Sodhi and Tang 2019) showed how the customer's perceived value for a product or a service and customer's willingness to pay increase when firms disclose information, for example, on the production process or the employees' working conditions. This enhances the need for supply chain traceability and transparency, especially in some kinds of industries that are more affected by social and environmental scandals.

For example, 3 M Company recently developed a new solution with blockchain on Microsoft Azure to improve customers' accountability and visibility across its supply chain, enhancing brand loyalty and increasing customer safety (Microsoft 2018). This solution also increases trust and real-time visibility among all supply chain members. It helps identify and prevent fraudulent products from entering the supply chains, which is a big concern, especially in the pharmaceutical industry, regarding high cost (to identify and replace counterfeit products) and customer safety. Furthermore, since blockchain technology can be used to track shipments throughout the supply chain, it allows customers to access in real-time all the information related to their order status as it moves from one stage to the following one, enhancing customers' experience.

Starbucks also launched a pilot project with Microsoft to share with customers information about the coffee they buy, including data about the farm their coffee comes from, intending to increase trust and especially attract the younger generations who are particularly sensitive to environmental and social aspects (Almeida 2020). Blockchain affects all kinds of transactions between a business and a customer, like payments and refunds, which, in this way, become faster, safer, and cheaper (Deloitte 2021). Blockchain can also help enhance customer loyalty and rewards programs that encourage repeat purchases and provide companies with invaluable insights into their customers' buying behaviors. On the other hand, it protects retailers from the risk of coupon fraud. An example comes from the Coupon Bureau, a non-profit organization connecting all stakeholders to the digital coupon offer file whose advisory committee also includes members of General Mills (Coupon Bureau 2021). Over the last decade, one of the biggest challenges for the coupon system has been the lack of security and trust and the absence of a unified centralized solution to validate offers. The solution is developing a common blockchain-based platform that provides a real-time secure log for all coupons. All stakeholders can then validate when coupons are redeemed securely (Pollock 2020). It can be concluded that blockchain technology would benefit the entire relationship with customer-business, improving the accessibility and accuracy of the information, increasing the speed and trust of transactions, and reducing costs while simultaneously guaranteeing a higher level of privacy protection.

4.1.6 Product returns and reverse logistics

Similar to what happens in the forward network, blockchain technology can be used to manage the reverse supply chain through tracking, visibility, and accuracy of information. Since blockchain creates a trusted environment through the integrity and immutability of its data, it can be applied to the resale marketplace, demonstrating the authenticity of products sold on second-hand markets and increasing trust among buyers. Walmart has just released a new patent that details a blockchain ledger to track items sold to customers. The system would allow a customer to register the purchase of an item and then choose a resale price, with the system acting as a digital marketplace (Pymnts 2018).

Blockchain can help deal with defective goods and product returns. An interesting example comes from the automotive industry— when a part is found to be defective, car manufacturers need to recall all the vehicles of a specific model and year because they cannot identify every part in every vehicle sold. It is usually very costly and harmful for the company, especially considering that the defective part can actually be fitted in just several hundred vehicles (for example, consider BMW's global recall of 1.6 million vehicles in 2018; Behrmann 2018). A blockchain-based system would allow the manufacturer to identify every single part of a vehicle and, in case of a recall, drastically save cost and time by recalling and repairing just the defective ones (Jones 2017). Blockchain can also mitigate the risk of fraud in product returns; in 2017, a woman cheated Amazon India for almost 900,000€. She was purchasing expensive electronic products from the company; simultaneously, she bought a cheap duplicate of the same product and then claimed refunds for Amazon's delivered products after returning the inexpensive duplicate (Petlee 2017). Implementing a blockchain system would prevent the possibility of returning a product different than the one originally purchased. Finally, blockchain can help track recycled material's origin and composition and prove its authenticity. Dell Technologies collaborates with software company VMware to track and trace the recycled components in its supply chain. Dell's supply chain has a strong presence in Southeast Asia, which is also responsible for 60% of ocean plastic (Insights 2019). In this way, Dell can create a circular economy by directly controlling and measuring the content of plastic entering the oceans.

On the other hand, customers can have information on the recycled material their laptop is made from and its origin. As already presented in Section 4.1.1, AbbVie has recently joined the MediLedger consortium in a blockchain project that enables participants to track and verify product authenticity. Another application of this project is to address the critical issue of saleable returns in the pharmaceutical industry—with a closed blockchain system, only manufacturers can attach unique identifiers to the products. At the same time, companies can verify anytime who touched what drug and at what time. As a result, returned items in the appropriate conditions may still be resold in total security.

Table 2 provides a visual summary of the key benefits and performance improvements deriving from the blockchain technology implementation at different stages of the supply chain. We reference the comparative case study for each supply chain process-measure combination.

4.2 The theoretical framework for blockchain implementation in supply chains

We next employ the findings from the qualitative research to develop a theoretical framework for blockchain-based supply chains. In particular, we match the blockchain technical characteristics (as described in Section 2.1) with the supply chain performance implications (identified from the case studies analysis in Section 4.1), following the value chain approach defined in Section 2.2. We report in Fig. 3 the theoretical framework proposed.

The top part of Fig. 3 is built based on the literature review and covers the characteristics of blockchain technology. Next, we match these characteristics across the supply chain processes (in the central part of Fig. 3) with the case studies. Specifically, we identify how case companies have used blockchain technology in their supply chains and its impact on their supply chain processes' performance. For example, we looked for the immutability characteristic of blockchain in all collected case studies and analyzed how and which supply chain processes it affects. A similar approach is used for the other characteristics. Finally, the bottom part of Fig. 3 presents the performance implications of blockchain technology implementation across the supply chain processes. These performance implications are derived primarily from case studies' analyses and supported by the literature (e.g., Di Vaio and Varriale 2020; Kumar et al. 2021; Difrancesco et al. 2022).

Table 2 Blockchain-driven supply chain performance improvements

Supply chain processes	Supply chain performances improvement after adopting blockchain technology					
	Cost	**Speed**	**Visibility & Transparency**	**Quality & Perceived Value**	**Trust**	**Sustainability**
Sourcing and Manufacturing	• Easier detection of errors and anomalies and contain the consequences *(Walmart)* • Reduce costs for users *(BMW)*	• Reduced interaction among parties and tracking time due to real-time, digitalized, and verified information *(Walmart)*	• Possibility to track components and verify information among parties *(Walmart, Starbucks)*	• Fast and easy detection of errors or quality issues *(Walmart)* • Ability to prove products required standards and legal compliance *(AbbVie, Pfizer)*	• Ability to prove the authenticity of a product to its stakeholders *(Starbucks, AbbVie, Pfizer)* • Easier detection and prevention of frauds *(BMW, AbbVie)*	• Improve food health safety due to product food supply chain tracking *(Walmart, McDonald's)* • Improve social impact through forced labor detection, workers' rights protection, and foster local markets *(Coca-Cola, Starbucks)* • Guarantee transparency on the sustainability of products and environmentally sound practices *(Nestle, Starbucks)* • Reduce congestion and pollution and improve safety *(BMW)*
Inventory Management	• Decrease inventory costs (over- and under-stock) due to better forecast, reduced errors, and data accuracy *(Nike)*	• Reduced interaction among parties and tracking time due to real-time, digitalized, and verified information *(Nike, Lenovo)* • Shorter throughput time because of faster detection of bottlenecks, disruptions, and other anomalies *(Lenovo)*	• All the SC partners have a real-time view of all the information about products and ownership *(Nike, Lenovo)*	• Fast and easy detection of errors *(Lenovo)* • The better service level provided to customers due to more accurate inventory records *(Nike)*	• Increased trust among SC participants because of higher transparency and verified transactions between parties *(Lenovo)* • Easier detection and prevention of frauds *(Lenovo)*	
Distribution and Delivery	• Decrease shipping cost due to lower/faster paperwork and real-time verified information *(L'Oréal)*	• Speed up paperwork and shipment process *(L'Oréal)* • Speed up delivery with blockchain identifiers *(Walmart)*	• Real-time tracking of products throughout the distribution process *(Alibaba, Walmart)*		• Increased trust among SC participants because of higher transparency and verified transactions and information between parties *(Alibaba, Walmart)* • Easier detection and prevention of frauds and increase customers' trust *(Alibaba, L'Oréal)*	

Table 2 (continued)

Supply chain processes	Supply chain performances improvement after adopting blockchain technology					
	Cost	**Speed**	**Visibility & Transparency**	**Quality & Perceived Value**	**Trust**	**Sustainability**
Retail	• Cheaper in-store and online transactions with customers *(Coca-Cola, Starbucks, Amazon)*	• Fast in-store and online transactions with customers *(Coca-Cola, Starbucks, Amazon)*	• Real-time tracking of products and information *(Walmart)*		• Increase customers' trust in the authenticity of products and in the environmental impact of the retailer *(Walmart, Unilever)* • Safe in-store and online transactions with customers *(Coca-Cola, Starbucks, Amazon)* • Protection against the risk of coupon fraud *(General Mills)*	• Improve food health safety due to product food supply chain tracking *(Walmart, McDonald's)* • Offer retailers the possibility to contribute to sustainability projects visibly and transparently *(Unilever)*
Customers	• Cheaper in-store and online transactions with customers *(Coca-Cola, Starbucks, Amazon)*	• Fast in-store and online transactions with customers *(Coca-Cola, Starbucks, Amazon)*	• Improve customers' accountability and visibility across the supply chain *(3 M)*	• Increase customers service and experience by providing accurate real-time information on their orders *(3 M)* • Enhance reward programs in a secure way *(General Mills)*	• Safe in-store and online transactions with customers *(Coca-Cola, Starbucks, Amazon)* • Increase customers' trust by detecting and preventing frauds *(3 M, Starbucks)*	• Enhance customers' safety by preventing fraudulent products from entering the supply chain *(3 M)*
Reverse Logistics		• Reduced time to collect any information concerning the reverse flow of material and detect any quality issue of fraudulent behavior *(Walmart, Dell, Amazon)*	• Possibility to track items after their sales to customers and the accuracy of information *(Walmart)* • Possibility to track components of recycled materials *(Dell)*	• Fast and easy detection of quality issues and managing the return of product defects *(BMW)* • Detect and prevent fraudulent product returns *(Amazon)*	• Increased trust from users of marketplaces *(Walmart)*	• Contributing to the creation of a circular economy by controlling and measuring hazardous components in returned products *(Dell)* • Safety for users in saleable returns *(AbbVie)*

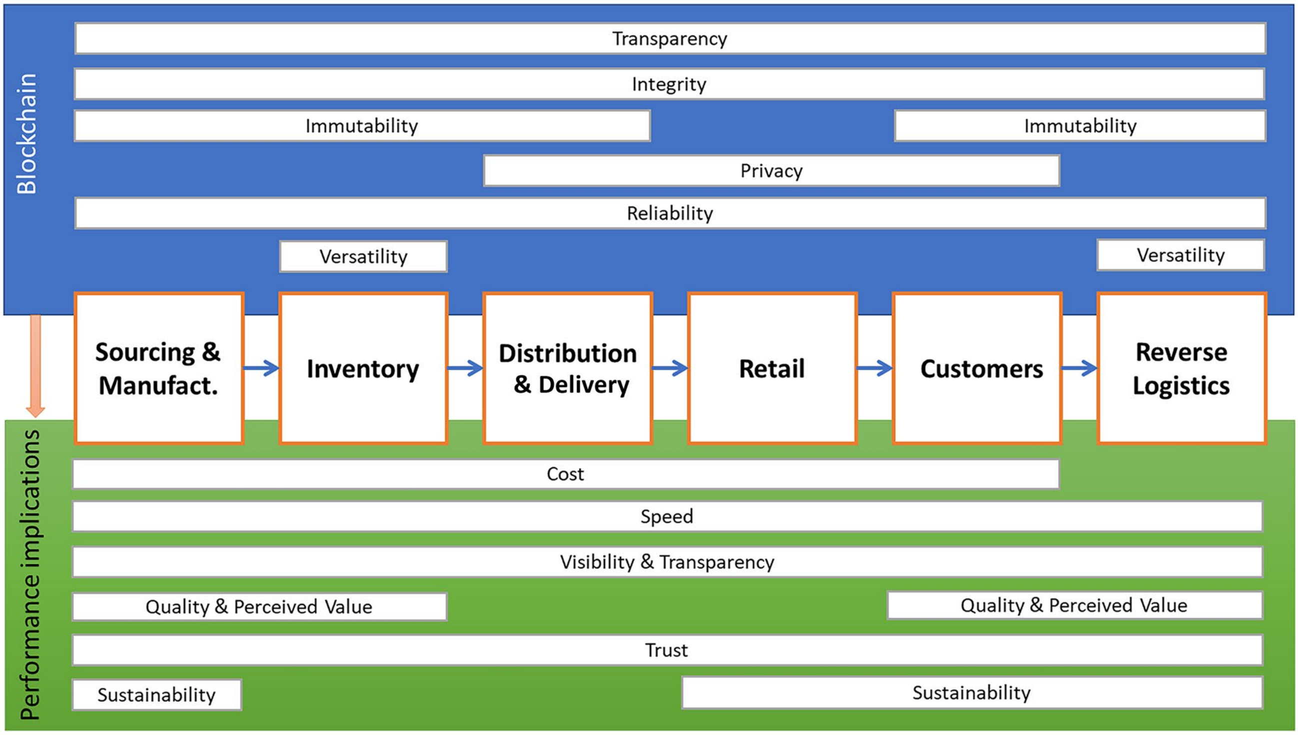

Fig. 3 Theoretical framework for blockchain implementation in supply chains

The analysis reveals that transparency, integrity, and reliability affect each stage of the supply chain and hence are the most relevant blockchain characteristics for supply chains. The results show that privacy is important for downstream supply chain members, such as distributors, retailers, and customers. The decentralized nature of blockchain offers privacy to supply chain members. The immutability of data mainly involves information related to the status and ownership of a product throughout the supply chain. Hence, it affects both the upstream (e.g., sourcing and manufacturing) and downstream (e.g., warehousing, distribution, and reverse logistics) supply chain processes. The versatility characteristic affects inventory and reverse logistics processes and allows supply chain members to integrate their own programs to improve their responsiveness to customers' needs (Seebacher and Schüritz 2017; Fernández-Caramés et al. 2019).

Concerning performance, it is found that blockchain technology can significantly improve supply chain performance. In particular, some of the most common benefits of blockchain implementation are the increase in trust, visibility, transparency, and speed, which affect all processes from the upstream to the downstream supply chain. Also, we note an important improvement in cost and quality at almost any stage of the supply chain. This finding is consistent with the literature (Zhou et al. 2022).

Moreover, blockchain technology can improve supply chain sustainability performance both upstream (in the sourcing phase) and downstream (involving the actors related to the reverse logistics process and sustainability awareness). The performance improvement is grounded in blockchain technical characteristics, especially the transparency, integrity, and reliability. Furthermore, it is observed that visibility, representing a major criticality in supply chains (Heese 2007; O'Marah et al. 2014; Buell et al. 2016; Deloitte 2021), can be restored thanks to blockchain.

5 Discussion and managerial implications

This section discusses the managerial implications of the results. It also presents the significant barriers and limitations in blockchain adoption. Our analysis reveals that blockchain implementation can largely benefit supply chains.

According to the theoretical framework and consistent with the literature (Baharmand et al. 2021; Liu et al. 2021), transparency, integrity, and reliability significantly affect all parties and related processes across the supply chain. These three characteristics of blockchain are vital for successful supply chains. The immutability characteristic of blockchain affects both upstream and downstream supply chain processes. Surprisingly, we did not find evidence of this affecting the retailing process. Privacy is a major concern, mainly for the downstream members of supply chains. It is a characteristic that primarily involves customers and those actors that–directly or indirectly–interface with customers (like retailers and distributors). Customers are indeed posing increasing attention to privacy issues and expect retailers to guarantee a high level of data protection. The versatility characteristic is important for parties who deal with inventory and reverse logistics processes. Supply chain members involved with these processes need more flexibility to adapt and respond to the dynamic demands of customers. With blockchain implementation, participants can integrate their own programs to quickly improve their responsiveness to customers' needs.

There are different indicators that affect the supply chain performance. As identified in the proposed theoretical framework (see Fig. 3), cost, speed, trust, visibility, and transparency are the most important performance indicators affecting most supply chain members. Similar to previous studies (Bumblauskas et al. 2020; Ada et al. 2021; Baharmand et al. 2021; Liu et al. 2021; Carlan et al. 2022), we find that blockchain helps decrease the cost and the time of sharing information and data among parties, making product visibility and tracking cheaper and easier. Further, as evident from the theoretical framework, inventory and warehousing costs can be reduced thanks to a truthful blockchain-based inventory system, which allows any parties in the supply chain to access the accurate inventory data and, therefore, optimize inventory policies while reducing stockout risks. Similarly, with blockchain implementation, cost and time related to the delivery process can be decreased since real-time trustable transactions can easily replace the associated paperwork. This aspect is becoming more and more relevant due to the globalization of supply chains and the frequent transshipment of cargo among different transportation modes and countries (Carlan et al. 2022). As a reference example, a single container shipped from East Africa to Europe may require up to 30 people to deal with the stamps and approvals (Popper and Lohr 2017). Knowing that about 90% of goods in global trade are carried by the ocean shipping industry each year (Mearian 2018), we can easily get a rough idea of how costly, time-consuming, and risky (e.g., documents lost or fraud) this can become. Additionally, a container can be stacked at port for days because of a missing paper, although the container can be loaded on a ship in a matter of minutes. Moreover, blockchain technology allows instantaneous, truthful, and cheaper payment transactions among supply chain parties (e.g., payment from customers or suppliers).

Furthermore, it is observed that visibility (especially as one moves far from the manufacturer) has been identified as one of the major issues in supply chains (Heese 2007; O'Marah et al. 2014; Buell et al. 2016; Deloitte 2021). Blockchain implementation can restore visibility, even while moving far from the manufacturer (retailer and customers). Also, blockchain enhances trust among supply chain parties, which is particularly significant if one considers the critical role of supply chain collaboration and trust among parties (e.g., Iyer and Ye 2000; Cachon 2004; Beske et al. 2014; Kumar et al. 2021).

Further, it is found that product quality and perceived customers' value are important in upstream and downstream supply chain processes. Blockchain technology offers the ability to prove that products comply with legal standards and requirements. Sharing accurate real-time information allows for fraud detection and prevention, decreasing the burden deriving from frauds in the supply chain, and early detection of bottlenecks, disruptions, quality issues, or mistakes at any stage of the supply chain. Since blockchain is characterized by the integrity and immutability of real-time data (see Fig. 3), it allows supply chain members to share real-time trustable information about products, ownership, and transactions at any time across the supply chain stages. With more visibility and transparency across the supply chain, members can also trace back to each component source to detect any required information or anomalies in a matter of seconds. Moreover, blockchain technology can improve customers' experience and perceived service level due to the accurate information that manufacturers, distributors, or retailers can provide to customers, e.g., on their order status or the available in-stock inventory. Also, with the help of blockchain, customers can be guaranteed the authenticity and the safety of the product they buy and securely reward programs. Improving the perceived quality of customers' experience is a key differentiator in today's global and competitive environment (Zhou et al. 2022), where customers continuously increase their expectations and demand for a fast, convenient, and fully integrated experience (Kopyto et al. 2020).

As inferred from our theoretical framework, when we enlarge the analysis encompassing more comprehensive performance measurements, blockchain can positively affect new indicators (i.e., sustainability). Results show that blockchain technology also improves sustainability by enhancing the traceability of products, improving quality, and detecting fraud. This finding is consistent with the literature (Di Vaio and Varriale 2020). Like in the forward supply chain, blockchain allows collecting any information concerning the reverse flow of materials, including the quality status and composition of returned products for resales/reuse and fraudulent behavior. It increases trust from reverse flow users and enhances the creation of a circular economy. At the same time, blockchain fosters sustainable initiatives for supply chains and customers' sensitivity to sustainability, providing the means to track every single product throughout the supply chain and verify its actual footprint. Social aspects such as forced and child labor detection, workers' rights protection, and customers' health and safety can be verified along with environmental issues. It can be concluded that blockchain technology has the potential to improve sustainable supply chain performance under a more holistic and triple-bottom-line point of view, moving from traditional performance indicators such as cost and speed to a more comprehensive performance measurement framework that includes trust, visibility, transparency, customers' experience, and sustainability.

Despite the great benefits of blockchain technology discussed so far, blockchain also comes with several drawbacks and entails risks and limitations. One intrinsic limit of blockchain derives from its young age. Since it is a relatively new technology, managers are often skeptical, especially when they have to invest a significant amount of money. As revealed by a recent survey conducted by Ernst and Young (2018), complex regulation is the most significant barrier to widespread blockchain adoption. Another important aspect required for the adoption of blockchain is that all parties should be involved in its adoption. For example, it would not be helpful if only one supplier implements blockchain technology while the other supply chain partners do not. Furthermore, another important issue is related to data protection and privacy concerns. For example, some countries' current privacy legislation (e.g., the European Union's new General Data Protection Regulation; GDPR 2018) requires that users have the right to request the erasure of personal data related to them (the "right of erasure", previously called the "right to be forgotten"). However, one of the main characteristics of blockchain is its data's permanency, which makes it impossible, at least in public systems, to follow this directive. Additionally, blockchain technology significantly impacts energy consumption and sustainability because of the high computing power required for its implementation and running. Furthermore, especially in global supply chain environments where suppliers are often located in developing countries, access to the required technology and energy supply can be prohibitive.

6 Conclusions and directions for future research

Most previous studies on blockchain applications in supply chains involve the upstream part of the supply chain (sourcing and manufacturing) and distribution. This paper complements the literature by addressing all supply chain processes, from sourcing to reverse logistics. Among these, we highlight the involvement of the central role of customers in supply chains, which has been identified as one of the major drivers in today's supply chains (Christopher and Ryals 2014; Ishfaq et al. 2016). Also, our focus on reverse logistics and sustainability answers the call for increasing attention to sustainability issues in global supply chains (Kumar et al. 2021; Difrancesco et al. 2022). Further, as opposed to isolated case studies, often focusing on the technical characteristics of blockchain, this study offers a holistic framework incorporating and matching the blockchain technical characteristics, its applications in the supply chain processes, and performance improvements.

This paper aims to help academics and practitioners understand and make strategic decisions on the design, implementation, and benefits evaluation of blockchain technology in different supply chain sectors. We conducted qualitative research by analyzing case studies related to the Gartner Top 25 list of companies. Each case study was analyzed following the Porter value chain approach. In particular, six core functions related to supply chain processes for blockchain applications were identified: sourcing and manufacturing, inventory management, distribution and delivery, retail, customers' experience, and product returns and reverse logistics. We then discussed the supply chain performance improvements deriving from adopting blockchain technology for each supply chain process. Next, a theoretical framework was built for blockchain-enhanced supply chain performance based on qualitative research results. Finally, the major drawbacks deriving from blockchain adoption were discussed.

This paper contributes to the emerging literature on blockchain technology applications in the supply chain area by providing structured qualitative research based on 20 case studies collected from different industries. We highlighted the implications, benefits, and challenges deriving from blockchain implementation and how blockchain technical characteristics tackle each supply chain process. This study's results show managers how blockchain can be implemented at any stage of the supply chain and unveils the relevant potential benefits of the supply chain performance metrics. In particular, blockchain implementation can help managers structure and improve their network of relationships among the supply chain partners, improve collaboration, and provide efficient, real-time, and trustable resource and information sharing. This research supports managers in making long-term, well-informed strategic decisions based on reliable data, investing in collaborative activities with other supply chain partners, and providing a better customer experience.

Moreover, due to its property of visibility, data integrity, and traceability, blockchain enhances the development of sustainable supply chains, particularly the environmental and social dimensions that represent a critical issue, especially in global and geographically dispersed networks. Managers should also be aware of the limitations and drawbacks of blockchain technology to evaluate the net benefit derived from its implementation. Similar to any other study, this paper also has some limitations. First, although based on well-recognized and solid supply chains, this study can be extended to encompass a larger number of companies. Second, although the identified case studies mainly focus on global companies, analyzing how our findings change when including local and small-medium enterprises would be interesting. Finally, due to the topic's novelty and the field's extremely dynamic nature, most companies are still at the very early stage of blockchain implementation or driving pilot projects. Therefore, we stress the need to continue working in this direction and monitor the projects' advancement over time to derive a deeper analysis and more robust results. More studies and research are expected on blockchain technology in the supply chain management field in the coming years. It is clear indeed that, despite the novelty of the topic and "regardless of the price of bitcoin, blockchain technology is here to stay" (Di Gregorio 2018).

Appendix

Table 3 The gartner supply chain top 25 for 2021

Rank	Company	Peer opinion (25%)	Gartner opinion (25%)	Three-year weighted ROPA (20%)	Inventory turns (5%)	Three-year weighted revenue growth (10%)	ESG Component score (15%)	Composite score
1	Cisco Systems	842	489	306.4%	13.6	–0.4%	10.00	6.37
2	Colgate-Palmolive	1217	557	65.9%	4.2	2.9%	10.00	5.58
3	Johnson &Johnson	1386	502	73.6%	3.0	1.8%	8.00	5.22
4	Schneider Electric	993	512	59.4%	4.9	–1.2%	10.00	5.07
5	Nestlé	1372	323	40.6%	4.2	–3.6%	10.00	4.41
6	Intel	687	421	37.0%	3.8	7.2%	10.00	4.40
7	PepsiCo	1003	351	43.0%	7.8	3.9%	10.00	4.37
8	Walmart	1668	311	15.3%	9.4	4.5%	8.00	4.23
9	L'Oréal	1062	234	69.9%	2.7	0.8%	10.00	4.05
10	Alibaba	1343	201	69.2%	20.9	44.4%	1.00	3.90
11	AbbVie	182	74	216.4%	4.4	22.5%	5.00	3.78
12	Nike	1189	249	33.1%	3.4	1.2%	8.00	3.60
13	Inditex	816	261	22.0%	3.8	–10.8%	10.00	3.51
14	Dell Technologies	614	293	30.4%	18.5	4.6%	8.00	3.47
15	HP Inc	343	281	45.7%	8.0	0.8%	10.00	3.46
16	Lenovo	465	343	18.8%	10.4	4.5%	8.00	3.40
17	Diageo	511	259	37.2%	0.8	–2.4%	10.00	3.36
18	Coca-Cola Company	1350	156	68.5%	4.0	–4.2%	6.00	3.34
19	British American Tobacco	187	102	96.5%	0.6	6.5%	10.00	3.13
20	BMW	733	195	18.5%	3.7	–0.5%	10.00	3.13
21	Pfizer	1006	202	40.5%	1.0	–3.3%	6.00	2.97
22	Starbucks	1022	179	30.2%	12.2	–1.4%	6.00	2.87
23	General Mills	317	95	55.3%	7.2	4.6%	10.00	2.83
24	Bristol Myers Squibb	91	29	79.8%	3.7	37.8%	6.00	2.80
25	3 M	765	175	50.9%	4.0	0.2%	6.00	2.78

Source: https://www.gartner.com/en/newsroom/press-releases/2021-05-19-gartner-announces-rankings-of-the-2021-supply-chain-top-25

The 5 "Masters" companies for the year 2021 are: Amazon, Apple, Procter & Gamble, McDonald's, and Unilever

Declarations

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