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Technological Innovation for Sustainability in the Agrifood Industry: Investigating Challenges, Opportunities and Impacts

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LIST OF ACRONYMS

Concept	Acronym
Alternative Food Network	AFN
Artificial intelligence	AI
Average Variance Extracted	AVE
Confirmatory Factor Analysis	CFA
Composite Reliability	CR
Community Supported Agriculture	CSA
Corporate Social Responsibility	CSR
European Space Agency	ESA
Farm Management Information Systems	FMIS
Industry 4.0	I4.0
Internet of Things	IoT
Knowledge Based View	KBV
Nonce	Number used once
Proof of Stake	PoS
Proof of Work	PoW
Resource Based View	RBV
Radio Frequency Identification	RFID
Structural Equation Modelling	SEM
Short Food Supply Chain	SFSC
Sustainable human resources management	SHR
National Agricultural Information System	SIAN
Sustainable supply chain management	SSC
Sustainable stakeholders' management	SST
Triple Bottom Line	TBL
Technological maturity	TMT
Technological skill	TSK
Technological strategy	TST
Value Triangle Business Model Canvas	VT BMC

*Acronyms are listed alphabetically.

INTRODUCTION

The agrifood industry has a fundamental role in ensuring global security and development. Indeed, agrifood companies are required to ensure the supply of food for a growing population while reducing environmental impacts and respecting stringent regulations aimed at guaranteeing the safety and accountability of agrifood supply chains. From this perspective, new solutions and effective management strategies are essential to optimize operations and balance the often-competing priorities of sustainability and profitability. Moreover, society's growing concerns about environmental and social sustainability issues present agrifood companies with key challenges. Firms must reconcile economic performance with a low environmental impact, reducing emissions and using natural resources responsibly (Latino et al., 2023). Companies are also required to enhance the transparency and accountability of agrifood supply chains (Hasan et al., 2024). This is important to ensure food safety and regain consumers' trust, which has been undermined by recent food scandals (Smith & McElwee, 2020). Beyond enabling consumers to make informed purchasing decisions, supply chain transparency is also essential to ensure compliance with regulations and sustainability standards (Moysiadis et al., 2023).

In this scenario, technological innovation may become one of the main drivers for the sustainable development of the agrifood industry. Innovative Industry 4.0 (I4.0) solutions may provide agrifood companies with the opportunity to innovate processes and business models and address long-standing sustainability issues. The smart farming paradigm emphasizes the disruptive effect that the adoption of innovative I4.0 technologies could have on traditional farming practices (Abbasi et al., 2022; Senturk et al., 2023). It represents an evolution of precision agriculture that moves beyond efficient resource management. In smart farming applications, real-time and site-specific data are used to monitor and support all agricultural activities, from the execution of field operations to product tracking at each stage of the supply chain. Consistently, several studies provide thorough reviews of the applications of I4.0 technologies in the agrifood industry (Amentae & Gebresenbet, 2021; Lezoche et al., 2020; Senturk et al., 2023). The most relevant technologies include the Internet of Things (IoT), big data, Artificial Intelligence (AI) and blockchain. Applications domains range from crop monitoring to resource management, to decision support, to product tracking.

However, the diffusion of I4.0 technologies in the agrifood industry remains limited, and the literature presents some crucial gaps. Indeed, the literature lacks studies investigating the impact of I4.0 technologies on the sustainability and performance of agrifood companies empirically. Most studies adopt a purely conceptual approach, reviewing applications, investigating opportunities, and providing implementation frameworks (Derakhti et al., 2023; Finger, 2023; Miranda et al., 2019). This enabled the identification of new applications and the investigation of advantages. At the same time, scholars devoted less attention to the analysis of challenges and barriers to technological innovation. Empirical inquiries and the analysis of real solutions are needed to return a faithful representation of the dynamics underlying the technological transformation of the agrifood industry. Several studies suggest that the adoption of I4.0 technologies in the agrifood industry may entail severe managerial complexities and lead to unexpected consequences (Christiaensen et al., 2021; Martin et al., 2022). Some scholars focus on technical limitations inherent to I4.0 technologies, such as poor interoperability, high power consumption, or privacy and data security issues (Kamilaris et al., 2019; Yadav et al., 2020). Others suggest the presence of managerial and organizational challenges, including high investment costs, resistance to change and lack of technological skills, among others (Khanna, 2021; Prause, 2021). Finally, some authors question the influence that the competitive and regulatory context can have on the decisions of agrifood companies to adopt innovative technologies (Amentae & Gebresenbet, 2021; Appleton & Holt, 2023). Despite this, contributions remain fragmented, and the lack of empirical evidence makes it difficult to evaluate the relationship between the benefits and costs of technological innovation in the agrifood industry, both from an economic and sustainability perspective. This is also crucial to determine the real impact of I4.0 technologies on the development of the agrifood industry and direct the attention of researchers on pressing open issues. Furthermore, this is important to support practitioners in the integration of technological innovations into the business models of companies in the agrifood industry.

Consistently, this thesis aims to help bridge this gap, moving from the analysis of the most relevant applications of I4.0 technologies in the agrifood industry, and culminating in a multi-faceted empirical investigation of the impact of innovative solutions in agrifood supply chains. The thesis presents four chapters, each advancing the overall research project by addressing specific research questions and moving from a high-level perspective to an in-depth investigation of the most relevant real-world applications. Consistently, the first chapter aims to lay the foundations of the research through a comprehensive review of the literature on technological innovation in the agrifood industry, addressing the following research question:

RQ1) What are the main applications of Industry 4.0 technologies in the agrifood industry, and how do technologies align with the characteristics of different agrifood supply chains?

Answering this question enabled the classification of technological applications based on application domains and provide a novel contribution. Specifically, the chapter presents three fundamental types of agrifood supply chains, characterized by their configurations, business models, and objectives. This allowed to reflect on how I4.0 technologies may affect the performance of each type of agrifood supply chain, by matching applications with supply chain characteristics. Results show that, depending on the business model and context, different types of agrifood supply chains can implement I4.0 technologies to achieve unique goals. The findings also stress the importance of considering the synergies between different technologies, to enhance flexibility and enable the achievement of higher-order objectives. Finally, the first chapter enabled a critical reflection on the existing literature, addressing the following research question:

RQ2) What is the state of the research on technological innovation for sustainability in the agrifood industry?

This allowed to synthesize the main findings and key themes, highlighting crucial research gaps and outlining possible research directions. These provided the foundation to define the next objectives of the thesis, ensuring a coherent progression and valuable contributions. Results show that scholars effectively explored the potential of I4.0 technologies for a variety of applications. At the same time, the literature focuses on the benefits of technological innovation, partly overlooking the organizational and managerial challenges. Indeed, literature lacks empirical studies, investigating the impact of the adoption of innovative technologies on real applications. In this, emblematic is the case of blockchain-based tracking systems, which despite the potential advantages, so far have found little success in the agrifood industry.

Aiming to help bridge one of the kay gaps highlighted in the previous chapter, the second part of this thesis focuses on determining the impact of I4.0 technologies on the social sustainability of agrifood companies. Compared to environmental and economic sustainability issues, the social sustainability dimension has so far received little attention. Many studies highlight the positive impact of I4.0 solutions on natural resource management, waste reduction, and increased efficiency (Latino et al., 2023; Vernier et al., 2021), while crucial social issues remain under-investigated, with the notable exception of products' traceability issues (Compagnucci et al., 2022; Dal Mas et al., 2023). These fall into a growing research stream connecting product traceability with issues of safety, transparency and accountability of agrifood supply chains. Furthermore, recent studies suggest that technological innovation could have profound consequences on the quality of labour, the accountability of supply chains, and the relationship of agrifood companies with consumers and external stakeholders (Prause, 2021; Weber et al., 2022). However, empirical evidence is lacking, and some authors even question the effectiveness of I4.0 technologies in addressing key social sustainability issues in the agrifood industry (Martin et al., 2022; Zscheischler et al., 2022). Chapter two helps to bridge this gap by answering the following research question:

RQ3) How does the use of I4.0 technologies affect the social sustainability of agrifood companies?

The study presented in the second chapter aims to answer this question by developing a theoretical model to assess the impact of I4.0 technologies on multiple facets of social sustainability within the agrifood industry. Recognizing the lack of established frameworks in the field, the research began by identifying suitable metrics and measures to structure the analysis. Companies' ability to use I4.0 technologies was modelled by referring to the concept of technological capability, a construct encompassing skills, strategy, and technological maturity.

At the same time, the effects of I4.0 technologies on social sustainability were investigated across three main areas: labour management, sustainable supply chain management, and sustainable stakeholders' management issues. Regarding labour management, the literature highlights that agricultural workers often endure harsh working conditions due to the unpredictability of climatic factors. Moreover, power and information asymmetries within agrifood supply chains frequently lead to significant inequalities among supply chain actors, making it essential to explore how I4.0 technologies can promote a more equitable distribution of value. Lastly, the growing demand from consumers and governments for greater safety, accountability, and transparency further emphasizes the role of advanced technologies in fostering trust within agrifood systems.

The theoretical model was tested using the Structural Equation Modeling (SEM) methodology, based on data collected from 116 Italian agrifood companies. From this perspective, Italy represents a significant case study due to its advanced industrialization, stringent regulations, and dynamic market conditions that challenge companies to innovate while ensuring sustainability. The results highlight the complexity of the relationship between technological innovation and the improvement of the social performance of agrifood companies. This emphasized the need to analyse how the adoption of innovative technologies can impact key aspects of sustainability in real-world contexts. Chapters three and four of the thesis build on this observation, focusing on the exemplary case of blockchain adoption in the Italian wine industry.

Specifically, chapter three provides an empirical investigation of the opportunities and challenges of the adoption of blockchain-based product tracking systems. These are considered among the most promising applications to address some key safety, and accountability issues of agrifood supply chains, although available literature lacks empirical evidence and in-depth analysis of real-world applications. Indeed, the ability to track food products throughout the supply chain is critical to ensuring quality, safety, and compliance with standards and regulations (Menon & Jain, 2021; Pakseresht et al., 2023). Agrifood products are particularly sensitive to parameters such as temperature or humidity and risk degrading rapidly during storage or transport (Khanna et al., 2022; León-Bravo et al., 2019). Product tracking allows firms to identify and recall harmful products before they reach consumers while limiting waste. Also, provenance and production methods are distinctive features of agrifood products, significantly affecting prices and consumers' choices (Milford et al., 2021; Soon & Wallace, 2018).

Chapter three aims to help bridge this gap by focusing on the adoption of blockchain technology in the wine industry. This is an exceptionally interesting scenario due to the unique product characteristics and the peculiar dynamics characterising wine supply chains (Del Rey & Loose, 2023; Dos Santos et al., 2021). Compared to most agrifood products, high-end wines are premium goods. This enables companies to establish strong brand identities, increasing prices and margins (Bandieri & Castellini, 2023; Carbone et al., 2023). At the same time, this caused the emergence of severe brand imitation, label adulteration, and deceptive blending issues (Adamashvili et al., 2021; Kang et al., 2023). Thus, wine companies need new solutions to ensure product authenticity, demonstrate compliance with regulations, and build trust relationships with consumers. It is in this context that the use of advanced product tracking systems could help wineries reconcile social responsibility and economic performance.

However, the diffusion of blockchain in the agrifood industry remains limited, as do applications in the wine sector. Several studies attempt to provide an explanation by pointing to persisting technical limitations of blockchain technology, including low throughput and scalability, high energy consumption, and security issues (Casino et al., 2019; Singh & Sharma, 2023). Furthermore, some studies suggest the presence of other important organizational and managerial obstacles, such as high investment costs, lack of technological skills, or lack of shared policies and regulations (Cordeiro & Olsen, 2021; Malisic et al., 2023). Despite this, the issue of blockchain adoption in the agrifood industry remains under-investigated. Many studies adopt a conceptual approach and stress advantages over potential challenges and drawbacks (Chowdhury et al., 2023; Menon & Jain, 2021). On the other hand, some authors focus on overcoming technical and regulatory limitations, neglecting key managerial and organizational challenges. As for the wine industry in particular, most studies focus on analysing isolated success stories, returning a somewhat biased perspective (Bandinelli et al., 2020; Brookbanks & Parry, 2022). This is amplified by the lack of inquiries analysing failed attempts at integrating blockchain tracking systems into agrifood supply chains. This may be explained by companies' reluctance to disclose failures, which makes it difficult to gauge the actual impact of blockchain adoption in the wine industry. Thus, chapter three aims to complement existing studies by answering the following research question:

RQ4) What are the drivers and challenges of adopting blockchain-based systems for SMEs in the wine industry?

To answer the research question, the chapter presents the results of a qualitative multiple case study analysis focusing on investigating small Italian wineries' perception of the opportunities and challenges of blockchain adoption. In contrast to previous studies (Danese et al., 2021; Silvestri et al., 2023; Tiscini et al., 2020), the multiple case study approach offers a more balanced perspective on the state of blockchain adoption in the Italian wine industry, enabling an unbiased investigation of challenges and opportunities. In this regard, the decision to focus on SMEs' perceptions aligns with the objective of providing an accurate representation of the current state of blockchain adoption in the Italian wine industry. From a theoretical standpoint, this is important to understand the impact of technological innovation in traditional agrifood sectors. Additionally, this investigation can help identify new elements of debate and initiate a discussion on the complexities entailed by technological innovation in the agrifood industry. As for practical implications, the inquiries presented in chapter three enable the identification of key requirements that blockchain-based tracking systems must possess to meet the needs of wine companies. This is useful to provide companies and policymakers with useful suggestions to facilitate and elicit blockchain adoption in the wine industry.

The findings show that beyond technical limitations, several managerial and organizational challenges hinder blockchain diffusion in the wine industry. These include companies' limited awareness of blockchain technology, lack of technological skills, over-dependence on external providers, and high investment costs, among others. At the same time, the study shows how the adoption of blockchain-based systems may provide wineries with new opportunities to enhance supply chain accountability, effectively market their products and build trusting relationships with governments and consumers. Finally, the chapter discusses the interventions that companies and governments can take to encourage blockchain adoption in the wine industry. An important role may be played by partnerships with research centres and an increase in government subsidies. The ability of technology providers to design solutions balancing performance and costs is also essential.

Finally, chapter four presents the results of a collaboration with the company Euro.Soft s.r.l. It describes the development and features of a blockchain-based tracking system specifically designed to meet the needs of SMEs in the wine industry. In this, the collaboration builds on the results of the study presented in chapter three, showing how to move from the identification of the requirements of blockchain-based systems to the development of a solution tailored to wineries' resources and capabilities. This is pivotal to reconcile theoretical analyses with the complexities and peculiarities characterising real-world applications. Furthermore, it represents a crucial step to advance the literature by exploring how innovative technologies can contribute to the sustainable development of the wine industry. Ultimately, the objective of chapter four is to answer the following research question:

RQ5) What are the strengths, limitations, and requirements for the effective development of blockchain-based tracking systems in the wine industry?

To address this question, the chapter provides a detailed analysis of the architecture, requirements, and features of a blockchain-based tracking system designed for the Italian wine industry. The chapter opens by describing the analysis and development phases of the blockchain system, followed by a concise but rigorous overview of the regulatory and technological landscape faced by Italian wineries. This is a critical step in understanding the specific needs and constraints of companies in the sector. Next, the chapter illustrates how blockchain adoption could transform wine supply chains, improving safety and accountability. Specifically, results suggest how wineries may leverage innovative blockchain solutions to comply with regulations while gaining a competitive advantage and strengthening the relationships between actors in the supply chains.

Finally, the chapter concludes by reflecting on the strengths, weaknesses, and limitations of the proposed solution, outlining possible future developments and implications regarding the adoption of blockchain systems in the wine sector and the agrifood industry as a whole.

Figure I.1 synthesizes the objectives, stages and activities of the research described in this thesis. The figure illustrates how, moving from an in-depth literature review, it was possible to connect the main applications of I4.0 technologies to the characteristics of three fundamental types of agrifood supply chains, identify literature gaps, and outline research directions. Subsequently, the figure shows how the next stage focused on developing and testing a theoretical framework to analyse the impact of I4.0 technologies on the social sustainability of agrifood companies. Finally, the third stage involved addressing a particularly relevant real-world case, namely the adoption of blockchain tracking systems in the Italian wine industry. From this perspective, the results suggest that, despite the tangible benefits that blockchain adoption could bring in terms of social and economic sustainability, several managerial and organizational challenges still hinder the widespread adoption of this technology. Ultimately, these aspects were analysed through the development of a blockchain-based system for product tracking in the wine industry.

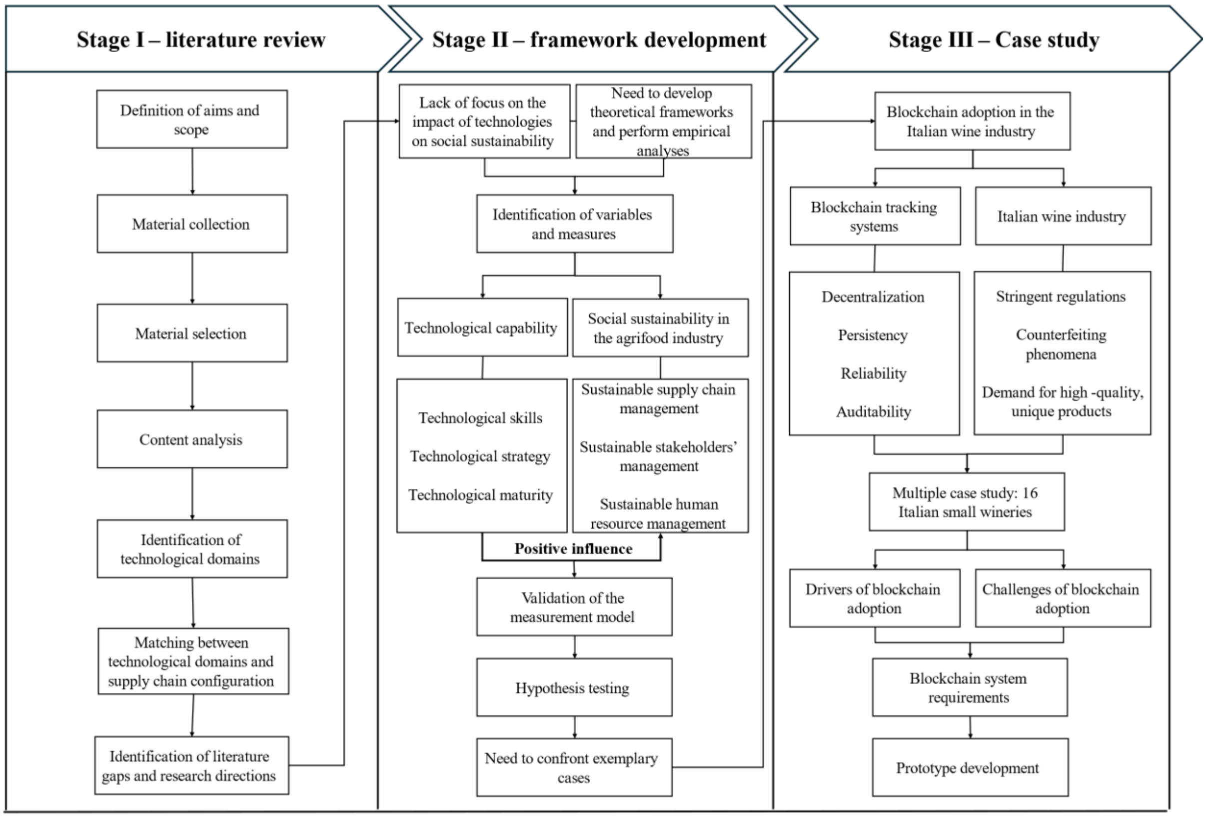


Figure I.1 flowchart synthesizing the main stages, objectives, and activities of the research project.

Overall, this thesis provides some important contributions. From a theoretical perspective, this research adds new elements to the literature. First, it highlights and analyses the relationship between I4.0 solutions, application domains, and characteristics of agrifood supply chains. Thus, it shows that despite having transversal impacts, I4.0 technologies can be used to achieve specific objectives that enhance the strengths and mitigate the weaknesses of different types of agrifood supply chains. Second, it helps to bridge the shortcomings of scientific literature in investigating the social impact of technological innovation in the agrifood industry, by developing and validating a theoretical model that can also be used as a reference for further studies. Third, it provides an in-depth analysis of the issue of blockchain adoption in the wine

industry, which is one of the most current and relevant applications of I4.0 technologies in the agrifood industry. From this point of view, the thesis provides a theoretical framework of the determinants of blockchain adoption in the wine industry, and an empirical analysis of drivers, challenges and requirements that a blockchain system must satisfy to meet wineries' needs.
As for practical implications, chapter one shows managers of agrifood companies that I4.0 technologies can provide key advantages, depending on the context and dynamics of the supply chain. Chapter two sheds light on the social implications of technological innovation in the agrifood industry, introducing nuance and complexity on a so far little explored topic. By focusing on the adoption of blockchain technology in the wine industry, chapter three contributes by identifying key requirements of blockchain product tracking systems, and by providing policymakers and practitioners with useful suggestions to elicit blockchain adoption. It is, however, in chapter four that the findings of the previous chapters lead to strong practical implications and enable the development of a blockchain solution tailored to the needs of SMEs in the wine industry. From this perspective, the chapter leverages the analysis of the challenges and drivers of blockchain adoption of chapter three to design an innovative product tracking system effective in the context of the Italian wine industry. Specifically, the chapter describes the architecture, the functioning and the main features of a blockchain-based system that can help small wineries combine supply chain control objectives with marketing efforts, in line with the Italian regulation in terms of product tracking and the most recent trends in the wine market.

CHAPTER I – Technological innovation in the agrifood industry

Summary

This chapter presents an overview of the most promising applications of I4.0 technologies in the agrifood industry and has a threefold objective. First, to provide a thorough literature review on the adoption of Industry 4.0 technologies in the agrifood industry, useful to outline the context of the thesis. Second, to analyse research gaps and trajectories, define the objectives of the thesis and lay the foundations for the investigations presented in the following chapters. Third, to capitalize on the literature review and provide a novel contribution. From this perspective, the chapter proposes a framework connecting Industry 4.0 technologies, their applications in the agrifood industry, and the objectives of different types of agrifood supply chains. This chapter is adapted from an article published in 2024 in the British Food Journal (Cricelli et al., 2024).

1.1 Introduction

In recent years, the issue of sustainable industrial development has become increasingly central to government agendas and consumer choices worldwide. Key issues include reducing the impact of production, creating more equitable supply chains, and reconciling economic goals with high environmental and social sustainability standards (Clapp & Ruder, 2020; El Bilali et al., 2021). This raised several issues and prompted serious reflections on the core dynamics of modern industrial systems. Among these, the agrifood industry has become the subject of a particularly heated debate, attracting the attention of institutions, practitioners, and scholars. From an environmental perspective, agrifood companies are required to manage scarce natural resources efficiently and responsibly, drastically reducing waste and emissions. As for social sustainability, the agrifood industry must safeguard consumer health, comply with stringent regulations, and increase supply chain transparency and accountability, meeting new consumers' and stakeholders' demands. Furthermore, companies in the agrifood industry are challenged to accomplish these goals while generating profits operating in an increasingly complex and competitive environment.

In this scenario, recent literature suggests that the adoption of innovative Industry 4.0 technologies may provide companies in the agrifood industry with the opportunity to innovate business models and significantly improve sustainability and economic performance (Annosi et al., 2020; Kamble et al., 2020; Lezoche et al., 2020). This is confirmed by the emergence of the expression Agriculture 4.0, which refers to the adoption of I4.0 technologies throughout the agrifood supply chain. This can be considered an evolution of precision agriculture, enabled by the introduction of I4.0 technologies and characterized by a wider scope of applications and advantages (Bongomin et al., 2020; Monteleone et al., 2020).

Compared to precision agriculture, which essentially refers to the use of site-specific cultivation techniques aimed at mitigating the waste of resources, the agriculture 4.0 paradigm is based on two key innovations, namely the centrality of data, and the flexibility of I4.0 technologies. Indeed, the main advantages of adopting I4.0 technologies in the agrifood industry stem from the ability to use real-time, site-specific data to support decision-making and improve activity planning. Data can also be used to monitor critical parameters throughout the supply chain, to ensure guarantee the quality of the products and the accountability of the chain. As for the technologies, numerous studies focus on analysing applications, advantages and synergies provided by different solutions. Specifically, some contributions provide detailed evaluations of technological alternatives, focusing on the performance evaluation of innovative I.40 technologies in the execution of specific tasks (Adhitya et al., 2020; Miranda et al., 2019).

Beyond the inquiries focusing on specific applications, literature reviews are also available. These contributions provide an overview of the different solutions, highlighting advantages and challenges. Among the most innovative solutions are applications based on the use of big data and artificial intelligence, on IoT, and blockchain-based tracking systems (Fu et al., 2020; Lezoche et al., 2020; Liu et al., 2021). While some studies focus on single technologies (Fountas et al., 2015; Kamilaris et al., 2019; Tzounis et al., 2017), others stress the advantages stemming from the integration of multiple solutions.

Overall, the literature provides an effective analysis of the opportunities and challenges of adopting I4.0 technologies in the agrifood industry. At the same time, several issues remain under-investigated. First, most studies adopt a technology-centric perspective, investigating the potential of innovative solutions for applications in the agrifood industry. While useful to clarify how technological innovation can help companies address key environmental and economic sustainability issues, these studies fail to investigate the full implications of adopting I4.0 technologies in agrifood firms and supply chains. Indeed, few studies propose implementation frameworks and even fewer take into account the specificities characterizing different types of agrifood supply chains or products. Second, the literature severely lacks empirical studies. From this perspective, the literature appears short of inquiries aimed at assessing the impact of adopting I4.0 technologies on the performance and sustainability of agrifood companies. Furthermore, few studies empirically investigate how adopting innovative solutions may change agrifood companies' business models, or how it could help firms address long-standing sustainability issues. Thus, this thesis aims to contribute to bridging these gaps by answering the following research questions:

RQ1) What are the main applications of Industry 4.0 technologies in the agrifood industry, and how do technologies align with the characteristics of different agrifood supply chains?

RQ2) What is the state of the research on technological innovation for sustainability in the agrifood industry?

To answer the research questions, this introductory chapter provides a concise yet effective overview of the main applications of I4.0 technologies in the agrifood industry. At the same time, this chapter attempts to enrich the literature by advancing a theoretical framework to understand how multiple technologies may affect the performance and dynamics of different typologies of agrifood supply chains. To this end, we leverage previous literature results to define a taxonomy of the application domains of I4.0 technologies in the agrifood industry. Subsequently, we combine these results with an in-depth analysis of the evolution and the characteristics of modern agrifood supply chains, to connect technological applications with the objectives and needs of agrifood supply chains.

Thus, a literature review on the applications of I4.0 technologies in the agrifood industry was performed. By bringing together the results of primary studies, this methodology enabled the systematization of knowledge on the opportunities related to the adoption of innovative technologies in the agrifood industry. This enabled a classification of I4.0 solutions for the agrifood industry based on application domains, thus answering the first research question. Furthermore, this led to systematising the main literature results, enabling the development of a theoretical framework illustrating the interplay between I4.0 applications and the characteristics of three, core types of agrifood supply chains. Finally, this enabled a reflection on the state of research on technological innovation for sustainability in the agrifood industry, highlighting gaps and opportunities for future research, thus answering the second research question.

Ultimately, this chapter provides three main theoretical contributions. First, it proposes a thorough taxonomy of I4.0 technologies based on application domains in the agrifood industry.

This helps clarify how the adoption of different I4.0 technologies may help agrifood companies address key environmental, social and economic sustainability issues. Second, it provides a theoretical framework to analyse how innovative technological solutions can complement the strengths and mitigate the weaknesses of different types of agrifood supply chains. This is essential to gain a more nuanced and pragmatic perspective on the implications of the adoption of I4.0 technologies in the agrifood industry and lay the foundations for much-needed empirical studies. Third, by reviewing available literature, this chapter sheds light on currently under-investigated research areas. As for practical contributions, this chapter provides managers and policy makers with a robust theoretical reference to assess how the adoption of specific technological solutions may impact the performance and sustainability of different types of agrifood supply chains, eliciting informed investments, and targeted interventions.

The remainder of this chapter is organized as follows: the next section presents the methodology used to review the literature, describing each step. Next, the main findings are summarized and discussed. In particular, a taxonomy of I4.0 technologies is developed based on the applications in the agrifood industry. The following paragraph offers a description and in-depth analysis of three main types of agrifood supply chains. Consistently, the paragraph discusses how different I4.0 technologies may affect each type of supply chain. The last section concludes by synthesizing the results and highlighting the contributions of the study. Finally, the main limitations are presented, and the foundations of the following chapters are laid.

1.2 Methodology

In this section, a systematic literature review of innovative applications of I4.0 technologies in the agrifood industry is performed. Literature reviews are secondary studies, useful to analyse and systematize the results of primary studies, which are based on direct investigations. These are useful when the body of primary studies on a topic grows exponentially, to synthesize available contributions, outline research trajectories, highlight key themes, and provide suggestions for future research. Given the prominence that technological innovation in the agrifood industry assumed in scientific production, the need for secondary studies has recently risen in priority. Consistently, several authors provided comprehensive and up-to-date reviews of applications of I4.0 technologies in the agrifood industry (Lezoche et al., 2020; J. Miranda et al., 2019; Saiz-Rubio & Rovira-Más, 2020). Differently from existing literature reviews, however, which mainly focus on analysing the state-of-the-art technological solutions for applications in the agrifood industry, this chapter aims to leverage results from primary and secondary studies to move one step further and analyse how innovative technologies may help agrifood companies address key environmental, social, and economic sustainability issues. To this end, we integrate two research streams, focusing on technological innovation and sustainable development of the agrifood industry. Thus, this chapter proposes a taxonomy of Industry 4.0 technologies based on application domains and provides an in-depth analysis of the characteristics and dynamics of different typologies of modern agrifood supply chains. Finally, this study combines this information to develop a theoretical framework connecting Industry 4.0 technologies, applications, objectives and challenges of different typologies of agrifood supply chains.

The methodology can be divided into three main phases, namely research design, material collection and selection, and framework development. Figure 1.1 presents key information on each phase. In particular, the preliminary research design phase led to the identification of literature gaps, the definition of the study objectives, and the development of a robust research methodology. The outcomes of this phase have been presented in the introduction and the present section. The following paragraphs present the subsequent steps.

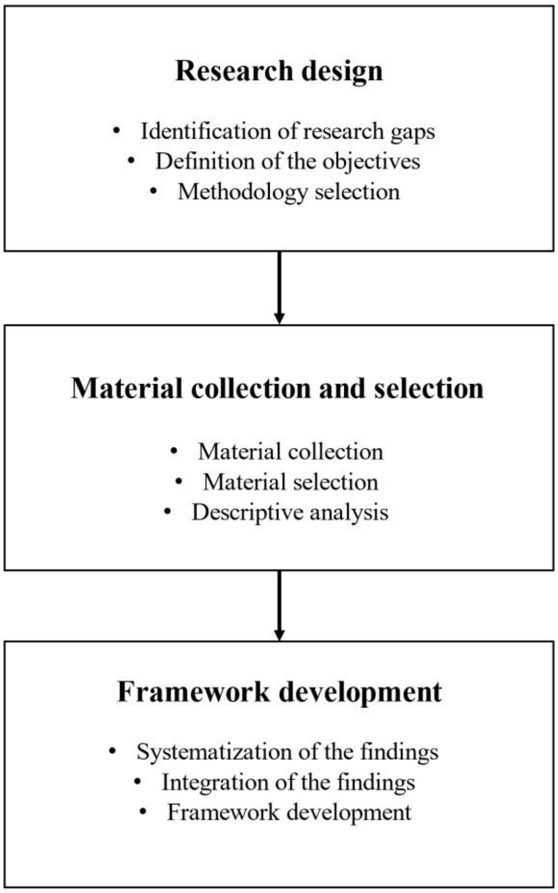


Figure 1.1 methodology.

1.3 Material collection and selection

1.3.1 Material collection

Although no unique standard for performing a literature review exists, scholars tend to agree on the steps required for the material collection and selection phases. As for this study, we followed the steps illustrated by Wong et al., (2013) and the guidelines provided by Baumeister and Leary, (1997) and Snyder, (2019). In the material collection phase, we scanned available literature using online databases of scientific publications Scopus and Google Scholar. These databases were chosen for their proven relevance across multiple disciplines and research fields (Bongomin et al., 2020; Testa et al., 2021). The material search was performed between September and November 2021. The string used for material search is the following:

(("Agriculture 4.0" OR "agriculture" OR "smart farming" AND NOT ("livestock" OR "fish *")) AND ("industry 4.0" OR "technolog*" AND "supply chain") OR ("supply chain "AND" development "OR" challenges "OR" evolution ")).

The primary objective of the search string was to enable the identification of articles investigating the adoption of I4.0 technologies in agriculture and agrifood supply chains. In this, the string was designed to include both works focusing on purely technological aspects, and publications with a broader perspective on the management of technological innovation in the agrifood supply chain. This laid the foundation for the integration of the findings of the studies. At this stage, it was also decided to narrow down the scope of the research, by focusing specifically on the analysis of the adoption of I4.0 technologies for applications related to the cultivation and production of crops, thus excluding the fishing and livestock industries. This choice was necessary due to the significant differences that exist between the use of I4.0 technologies for cultivation purposes and livestock activities. Furthermore, by limiting the scope of the investigation, the study allowed for more detailed and in-depth analyses.

1.3.2 Material selection

As for the material selection, this study only includes journal articles, conference proceedings and book chapters in English. Grey literature and other non-peer-reviewed publications were excluded from the sample, to ensure the quality of the contributions. Next, appropriate inclusion/exclusion criteria were defined, to select only the studies relevant to the objectives of the research.

The article selection process was conducted by three researchers. First, shared selection criteria were defined. Next, two researchers collaborated in the selection of articles. In the case of divergent opinions, the third researcher acted as a mediator. Excluding duplicates, the string material search activity returned 1.578 matches. The first selection criterion led to the inclusion of only studies cited at least once. This allowed to reduce the sample focusing on the most relevant works. At this step, 418 studies were excluded. Next, among the remaining contributions those pertaining to the subject areas: "chemistry", "biology", and "energy sciences" were excluded, as they were considered outside the scope of the investigations. This led to the exclusion of 477 articles. In the next step, the titles and abstracts of the remaining 683 studies were examined to exclude irrelevant contributions. In particular, studies were included only if they mentioned at least one specific application of an I4.0 technology in the agrifood industry. 436 studies were excluded at this stage. Finally, the selection was refined by reinforcing this criterion through the full reading of the 247 remaining contributions. Specifically, only articles analysing the impact of innovative technologies on agrifood supply chains, in terms of economic or sustainability performance. This was a key requirement to enable the identification of application domains and to connect technological applications with the objectives and characteristics of agrifood supply chains. 153 studies were excluded at this stage, leading to a final sample comprising 94 articles. Table 1.1 summarizes the material selection phase, highlighting inclusion and exclusion criteria.

Table 1.1 material selection.

Selection criteria	**Objective**	**Sample**
Results from the search string	Select studies that focus on the issue of technological innovation in the agrifood industry	1.578
Selection based on the number of citations	Enhancing the quality of the sample, by selecting only studies with at least one citation	1.160
Selection based on subject area	Refining the sample by selecting only the studies in line with the objectives of the research	683
Selection based on title and abstract read	Refining the sample by selecting only the studies mentioning at least one specific application of I4.0 technologies in the agrifood industry	247
Selection based on full read	Refining the sample by selecting only the studies analysing the impact of I4.0 technologies on agrifood supply chains.	94

1.3.3 Descriptive analysis

The temporal trend of the publications, shown in figure 1.2, suggests the growing interest of scholars in the topic of technological innovation in the agrifood industry with a clear increase in publications in the two years 2019-2020.

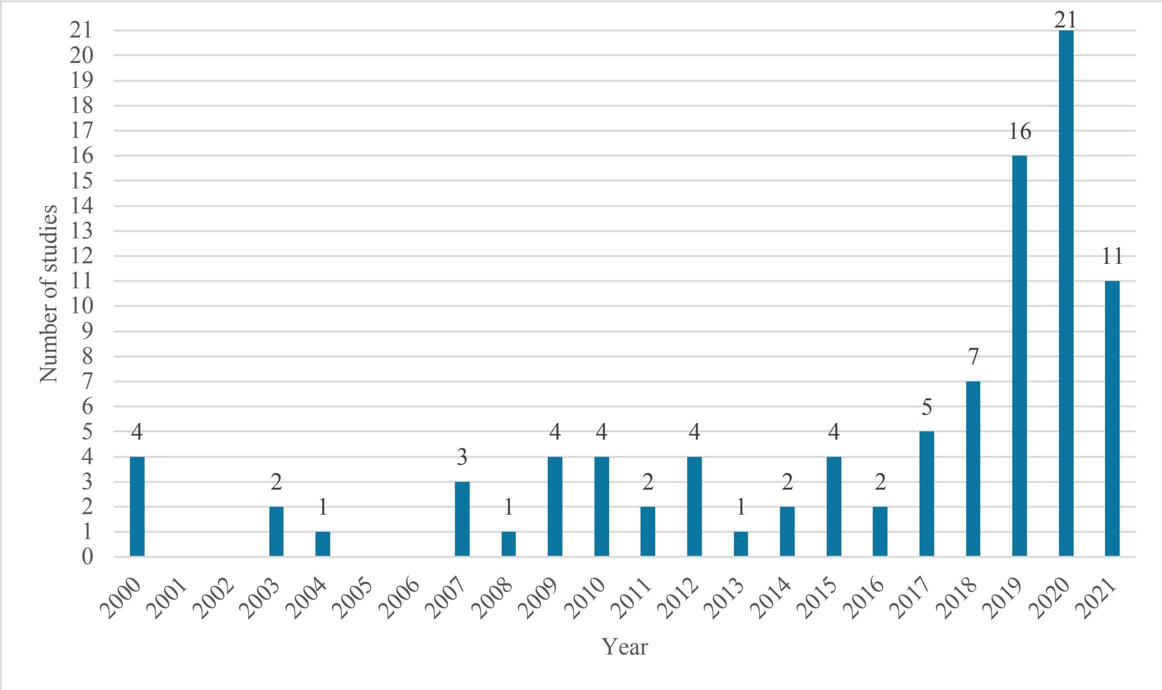


Figure 1.2 temporal trend of publications.

Furthermore, it is possible to observe an evolution of the research filed over time, as older studies usually show a broader focus, addressing the problem of sustainable technological development of the agrifood industry from a broader perspective. Meanwhile, recent studies tend to focus on the agriculture 4.0 paradigm, analysing specific applications of I4.0 technologies in the agrifood industry. As for the sources, the 94 studies included in the review were published across 69 journals, conference proceedings and books. However, only 12 journals host two or more studies. These are specifically devoted to disseminating studies discussing technological, engineering and IT issues. Consistently, it’s worth noting the absence of a journal focusing on exploring the issue of technological innovation in the agrifood industry from a managerial and organizational perspective. The most relevant journals are Computers and Electronics in Agriculture (8 articles) and Sensors (6 articles). The most relevant subject areas include Agricultural and Biological Sciences (indicated by 6 journals), Computer Science (5 journals) and Engineering (3 journals). Table 1.2 provides an overview of the most common subject areas, with an indication of the most relevant journals. Transdisciplinary journals may be associated with multiple subject areas.

Table 1.2 journals classification by subject areas.

Subject areas	**Journals**
Agricultural and Biological Sciences	Computers and Electronics in Agriculture Agronomy Precision Agriculture British Food Journal International Food and Agribusiness Management Review
Biochemistry, Genetics and Biology	Sensors
Business, Management and Accounting	British Food Journal International Food and Agribusiness Management Review International Journal of Information Management
Chemistry	Sensors
Computer Science	Computers and Electronics in Agriculture Computers in Industry IEEE Access International Journal of Information Management Sensors
Decision Sciences	International Journal of Information Management
Earth and Planetary Sciences	Remote Sensing
Energy	Sustainability
Engineering	Computers in Industry IEEE Access Sensors
Environmental Sciences	Sustainability
Materials Science	IEEE Access
Social Sciences	Sustainability International Journal of Information Management

Lastly, the articles can be classified following the methodology or research design adopted. From this perspective, research chapters include two sub-categories. The first comprises empirical studies focused on designing and assessing the performance of innovative technologies in the execution of specific tasks. The second includes articles analysing the evolution of the agrifood industry and the characteristics of different types of supply chains. Interestingly, quantitative empirical studies focusing on assessing the costs and benefits of adopting I4.0 technologies in the agrifood industry are lacking. Also relevant is the presence of literature reviews, which on the one hand stresses the need to systematize this rapidly growing body of knowledge, and on the other suggests the presence of several unexplored areas of research. Figure 1.3 shows the classification of the documents based on study typology.

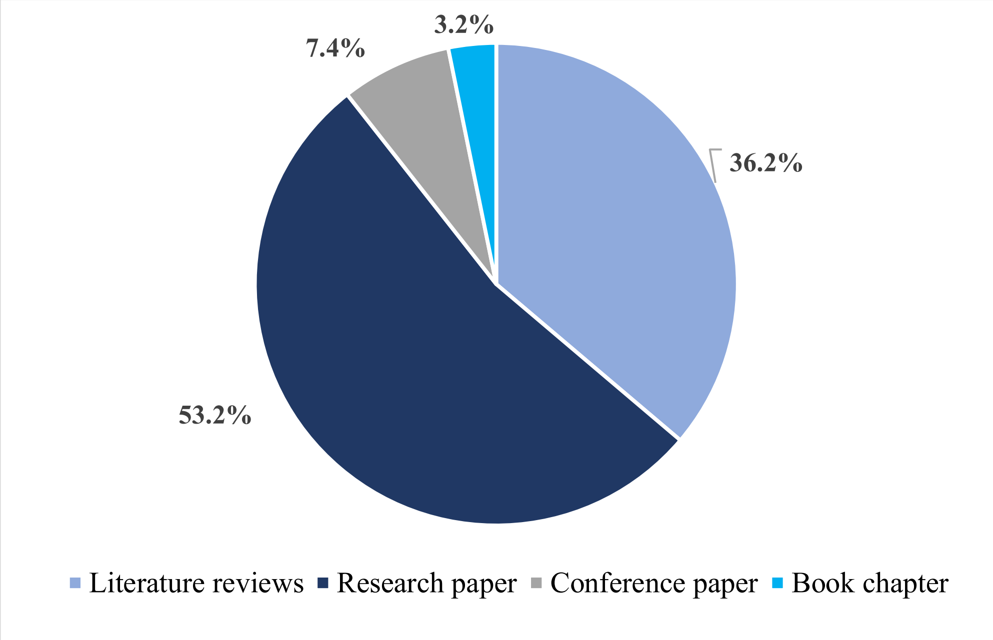


Figure 1.3 documents classification by typology.

1.4 Results

1.4.1 Industry 4.0 technologies in the agrifood industry

The synthesis of the knowledge from the reviewed articles allows to analyse the adoption of I4.0 technologies in the agrifood industry with respect to application domains. These represent sets of applications supporting specific activities and providing a coherent set of benefits. Thus, I4.0 technologies can be grouped into four main clusters, each linked to a particular application domain. Beyond providing a reasonable criterion for the classification of I4.0 technologies, the application domains allow to connect technological applications with the advantages provided to agrifood companies, and with their sustainability and economic objectives. Specifically, while the advantages relate to the execution of specific activities or tasks, the objectives are more broadly defined and depend on the characteristics and dynamics of different types of agrifood supply chains. For example, the main benefit of adopting a smart irrigation system is the optimization of water consumption. This can help the company achieve the goal of reducing the environmental impact of production. To pave the way for the identification of the main clusters, this section provides a synthetic overview of the main I4.0 technologies and their most relevant applications in the agrifood industry:

- Big data: the term does not refer to a specific technology, but rather indicates the ability to acquire and process large volumes of data in real-time, to support decision-making processes. Indeed, rapid technological advances overcame previous limitations in the ability to generate and process data, leading to the emergence of big data applications (Lytos et al., 2020). These are characterized by the volume, velocity, variety, veracity and value of the data (Kamilaris et al., 2017; Raut et al., 2019). The volume emphasizes the large amount of data generated, and velocity refers to the high processing rates. Variety indicates the heterogeneity of data sources and formats. Veracity underlines the reliability of the statistical outcomes obtained from the processing of a sufficiently large and complete data set. Finally, value stresses the potential usefulness of the information provided by big data applications, however subordinate to the ability to transform information into effective knowledge (Dubey et al., 2019). Consistently, the literature suggests that big data in the agrifood industry is mainly used for the definition of predictive models to support decision-making, activity planning and crop management (Saiz-Rubio & Rovira-Más, 2020; Wolfert et al., 2017). On this note, it's worth noting how big data applications require integration with other I4.0 technologies, including AI and IoT systems.

- Internet of Things: also in this case, rather than referring to a specific technology, the expression Internet of things can be used to indicate a smart system using appropriate devices to connect real elements through the internet (Elijah et al., 2018). For example, a sensor network can be used to set up a smart irrigation system capable of supporting agrifood companies in managing water resources (Monteleone et al., 2020). From this perspective, IoT applications pair with the exploitation of big data and show a clear connection with the concept of smart farming (Manogaran et al., 2021). Some of the most relevant applications of IoT systems in the agrifood industry relate to the setup of smart systems for irrigation or monitoring of soil and crop conditions. Other solutions concern the monitoring of environmental conditions or the state of machinery (Muangprathub et al., 2019). Finally, particularly promising is the utilization of IoT systems in combination with smart sensors and Radio Frequency Identification (RFID) tags for product tracking applications (Khanfar et al., 2021). These focus on real-time monitoring of critical crop parameters, including temperature and humidity, during storage and transportation, and are essential to ensure the quality of products reaching consumers.
- Artificial intelligence: AI-based solutions in the agrifood industry involve mainly machine learning applications. These are artificial intelligence applications where a large dataset is used to train electronic devices to perform specific tasks autonomously

(Liakos et al., 2018; Mavridou et al., 2019). Furthermore, performance can be optimized by teaching machines to execute tasks according to stringent criteria implemented through unique algorithms. In the agrifood industry, these applications are relevant to support cultivation activities and relieve human operators from performing simple but repetitive tasks. For example, machine learning can be used for crop counting and identification (Hrustek, 2020). Other common objectives are yield prediction, disease identification, and species recognition (Mavridou et al., 2019).

- UAVs and drones: These are primarily used for crop monitoring. Due to their relatively low cost and ease of use, these solutions are emerging as a viable alternative to satellite monitoring systems. Other applications include support for precision agriculture activities, such as weed mapping, plant identification, vegetation growth monitoring, and crop spraying applications (Matese et al., 2015; Tsouros et al., 2019; C. Zhang & Kovacs, 2012).
- Blockchain: can be thought of as a distributed electronic ledger, shared among participants of a network (Kamilaris et al., 2019; J. Xu et al., 2020). Participants can issue transactions, which are verified according to predefined criteria, and then appended to the blockchain. A unique chain of verified transactions is created, and the information on the ledger is updated. Each participant has visibility of the transactions that occurred in the network, while the privacy of the actors involved in the transactions is protected through cryptography (Khan et al., 2021; Macrinici et al., 2018). Compared to traditional ICTs, blockchain-based systems provide considerable advantages in terms of security, reliability, and transparency. In recent years, blockchain-based systems moved beyond financial applications and became among the most promising solutions to enhance the security, transparency, and accountability of supply chains (Dutta et al., 2020; Motta et al., 2020). This may prove particularly beneficial for applications in the agrifood industry, which is facing strong pressure from institutions and consumers. The need to ensure the safety of agrifood products, and the shortcomings of quality control schemes motivate the use of blockchain systems for product tracking applications (Antonucci et al., 2019; Patelli & Mandrioli, 2020). These could help agrifood companies address long-standing sustainability and economic issues. Indeed, product tracking is key to ensuring product safety, complying with regulations, reducing waste, and providing reliable information to consumers (Menon & Jain, 2021; Stranieri et al., 2021). Lastly, several authors also mention the potential of blockchain-based systems as a means to enhance coordination in supply chains, reducing transaction costs and

helping to reduce power and information asymmetries (David et al., 2022; Zhao et al., 2019).

- Radio Frequency Identification (RFID): regarding applications in the agrifood industry, this technology is used primarily for product tracking. Specifically, tags or bar codes can be applied to batches of products to ensure their rapid and efficient identification. These technologies can be used in combination with IoT systems or blockchain-based solutions to set up more advanced product tracking systems. Indeed, Bhutta and Ahmad (2021) observe how the combination of RFID tags, sensors and IoT allows the setup of wireless sensor networks for data acquisition and processing. These systems are mainly used for livestock and plant identification, parameter monitoring and product tracking.
- Farm Management Information Systems (FMIS): these are specialized information systems defined by Sørensen et al. (2010) as: "a planned system for the collection, processing, storing and dissemination of data in the form of information needed to carry out the operations functions of the farm". FMIS typically feature three main modules, namely a warehouse module, a processes module, and an administration module (Mazzetto et al., 2019; Saiz-Rubio & Rovira-Más, 2020). The warehouse module supports inventory management and helps streamline inbound and outbound product flows. This is especially important due to the limited lifespan of agrifood products and their sensitivity to environmental parameters during storage and transportation. The processes module supports the execution and planning of cultivation, processing and logistics activities. Indeed, careful planning of field operations enables the efficient management of natural resources and provides significant advantages in terms of labour management (Tummers et al., 2019). Finally, the administration module assists financial and sales management. In more advanced applications, farm management systems can be used in combination with smart systems to obtain real-time, site-specific data and develop more precise decision-making models (Liakos et al., 2018).

1.4.2 Application domains of Industry 4.0 technologies in the agrifood industry

After briefly reviewing the most relevant I4.0 technologies in the agrifood industry, this section groups the technologies based on application domains. These group the technologies according to the uses and benefits provided. Thus, four main clusters have been identified. It's worth noting that, due to their inherent flexibility, the same technologies can appear in multiple clusters, if they can be used to achieve different objectives.

- Monitoring and control. This cluster groups the technologies used to monitor key environmental, soil, or crop parameters. The technologies in this cluster can be used in both cultivation, storage and transportation activities (Liu et al., 2021; Tsouros et al., 2019). In the cultivation phase, smart sensor networks can be used to keep plants' health and growth parameters in check (Kamilaris et al., 2017; Kodan et al., 2020). Machine learning and AI solutions can also be used to simplify product counting and identification or to promptly detect the insurgence of pests and diseases (Fracarolli et al., 2020; Liakos et al., 2018). IoT systems connect the sensors and allow the transmission and elaboration of the data. The main advantages relate to yield maximization and field operations' planning (Lezoche et al., 2020; Oltra-Mestre et al., 2021). As for logistic applications, the use of IoT systems and smart sensors allows the monitoring of product quality parameters in real-time. The most interesting applications concern fresh produce and cold storage supply chains. In these instances, it is vital to monitor parameters such as temperature and humidity to ensure product safety, avoid losses and prevent low-quality products from reaching consumers.
- Resource management. The second cluster brings together I4.0 technologies that enable more responsible and efficient management of resources at the cultivation stage. This cluster focuses on applications relating to the core ideas of the "precision agriculture" paradigm (dos Reis et al., 2020; Mazzetto et al., 2020; J. Miranda et al., 2019). In it, the acquisition of real-time, site-specific data allows targeted interventions in different field management zones. This enables the ad hoc management of different crops, as well as the unique management of different areas within the same field. In these applications, a large amount and variety of data are collected using smart sensors, IoT systems or drones (Huang et al., 2018; Kamble et al., 2020; Wolfert et al., 2017). Data is then aggregated and processed using big data analytics, to develop accurate decision-making models. Some of the most common and relevant applications support the efficient utilization of chemicals and water resources.

  In particularly advanced applications, data can also be fed to AI-based systems to allow the autonomous execution of specific tasks. This allows the targeted use of pesticides and chemical agents (Fracarolli et al., 2020; Kamilaris & Prenafeta-Boldú, 2018; Mavridou et al., 2019). These applications are particularly relevant to support mass cultivation, where manual field management is impractical, and efficient resource utilization is key to generating savings, reducing waste, and limiting the impact of production activities.

- Product identification and tracking applications. The third cluster essentially includes solutions based on the combination of Blockchain technology with identification technologies, such as RFID tags, aimed at tracing and ensuring the quality of agrifood products throughout the supply chain (Antonucci et al., 2019; Rana et al., 2021). In general, these systems may help agrifood companies achieve two main objectives. First, they help simplify and streamline product flows. This is essential to reduce waste and the risk of unsafe products reaching consumers (Bhutta & Ahmad, 2021; Sunny et al., 2020). These solutions are particularly suited for applications in multi-tier supply chains, where the number of actors, the complexity of relationships, and large distances pose serious logistical and commercial challenges. The second objective concerns the certification of products' origin and properties. This may enable agrifood companies to adopt product differentiation strategies, enhancing brand identity and product quality (Ostfeld et al., 2019; Santeramo & Lamonaca, 2020). This can also help small, local firms gain visibility and access the market by targeting specific customer segments. Furthermore, the ability to certify products' origin and features may simplify access to markets with stricter rules, such as the EU. This is particularly important for supply chains that stretch beyond national borders and supply highly processed goods.
- Process coordination and information management. The fourth cluster groups technologies aimed at improving the transparency, coordination and accountability of agrifood supply chains. In the cultivation stage, big data can be leveraged by specialized farm management systems to define predictive models and support decision-making (Liu et al., 2021; Manogaran et al., 2021). For example, data on weather conditions and soil characteristics can be used to plan field the execution of operations and schedule subsequent activities. At the same time, data on inventories can be used to plan harvests and shipments, while data on market conditions can be used to set prices (Mazzetto et al., 2019; Saiz-Rubio & Rovira-Más, 2020). That said, given the pervasiveness of ICTs throughout the supply chain, an in-depth analysis of the multiple uses of these technologies throughout agrifood supply chain is not only impractical but is also beyond the scope of this study. On the contrary, through the definition of this cluster, the study intends to stress the relevance that modern information systems based on the use of I4.0 technologies have for information management in agrifood supply chains. On this note, it is worth noting how farm management systems can also prove particularly useful for SMEs and small farmers. Access to more detailed information and decision-making

support can increase SMEs' awareness of supply chain dynamics and help small companies reduce their reliance on large distribution groups.

Table 1.3 provides an overview of the four clusters, presenting the technologies associated with each cluster and the corresponding advantages for the company. The same technology can appear in different clusters if the relevant applications span multiple application domains.

Table 1.3 application domains of Industry 4.0 technologies in the agrifood industry.

Technological cluster	**I4.0 Technologies**	**Advantages**	**Objectives**
Monitoring and control	Internet of things. Big data. UAVs / Drones. Smart sensors networks. Machine learning /Artificial Intelligence.	Monitor plant growth parameters. Simplify product counting and classification. Identify weeds and diseases. Monitor temperature/humidity.	Maximize yield. Plan field interventions. Reduce product losses and waste. Ensure product safety.
Resource management	Internet of things. Big data. Machine learning / Artificial intelligence.	Determine crop water requirements. Analyse soil properties. Identify weeds and diseases.	Improve resource management. Generate savings. Reduce emissions and pollution.
Identification and tracking	Blockchain. RFID tags / Bar codes / QR codes.	Simplify transactions' validation. Certify product origin and properties. Determine responsibilities. Comply with international standards /regulations.	Differentiate products from competitors. Target different customer segments. Set higher prices. Access international markets.
Process coordination and information management	Farm management systems / IT software. Big data.	Streamline product flows. Facilitate information management.	Improve supply chain coordination. Reduce throughput time. Enhance SMEs autonomy.

1.5 Framework development

This section provides an analysis of how I4.0 technologies may help companies in the agrifood industry reconcile sustainability and economic performance. In particular, the classification of technologies according to application domains is used to connect technological applications with the objectives of different types of agrifood supply chains. Three types of agrifood supply chains have been identified. These differ in terms of product typology, scale of operation, key activities and core dynamics. While each technology may offer advantages to every type of supply chain, the focus will be on identifying the technologies that can best complement the strengths and mitigate the weaknesses of each configuration. Before presenting the three fundamental types of agrifood supply chain, however, it is useful to provide a brief overview of the characteristics and evolution of the modern agrifood industry, to clarify the context and assumptions supporting the analysis.

1.5.1 Evolution and characteristics of the modern agrifood industry

The modern agrifood industry presents a highly industrialized configuration, based on mass production logic, and the standardization of processes and products. According to Van der Ploeg (2010), the origins of the modern agrifood industry date back to the rapid economic development following the Second World War. Indeed, population growth and the spread of high standards of well-being made it necessary to efficiently produce ever-increasing quantities of food. In this context, rapid technological advances allowed to address the demands of society and the requests of governments, leading to the affirmation of a productivist model, aiming at cost reduction and maximization of yields (Clay & Feeney, 2019; Van Der Ploeg et al., 2017). Differently from other manufacturing industries, however, the agrifood sector is characterized by a higher level of uncertainty due to a series of uncontrollable and product-related factors. Among these are climatic conditions, seasonality of production and sensitivity of most products to environmental parameters, such as temperature or humidity (Bhutta & Ahmad, 2021; Elahi et al., 2021). Despite this, the productivist model succeeded in ensuring the supply of large quantities of food at very low costs. However, this model recently entered a crisis. Van der Ploeg (2010) identifies three interrelated causes of the “food crisis”. First is the ongoing industrialization of the agrifood industry, which led to the standardization of products and processes, and to intense price-based competition (Graubner et al., 2021; Mizik, 2021). Second, is the emergence of a global market for agrifood products, which further exacerbated competition and posed key challenges related to the monitoring and tracing of perishable products throughout worldwide supply chains (Vilas-Boas et al., 2023). Third is the affirmation of large distribution and sales groups that dictate market conditions and control supply chains by influencing upstream players and small farmers (Bonanno et al., 2018; Sexton & Xia, 2018). In response to the crisis of the traditional model, alternative agrifood supply chains are emerging, known as Alternative Food Networks (AFN) or Short Food Supply Chains (SFSC) (Rosol & Barbosa, 2021; Sacchi et al., 2022; Zambon et al., 2019). These models show a substantial redefinition of the configuration of agrifood supply chains. As the name suggests, SFSCs are short supply chains, characterized by few levels and targeting a market geographically close to the places of production. On the one hand, this increases the influence of upstream actors and small farmers, who are less dependent on large distribution groups. On the other, this allows producers to focus on differentiation strategies, leveraging the origin and provenance of products (Rogerson & Parry, 2020; Soon & Wallace, 2018). Furthermore, this also allows to mitigate the importance of efficiency and cost reduction, reconnecting farmers with customers and market demands.

1.5.2 Industry 4.0 technologies and agrifood supply chain configuration

After outlining the characteristics and evolution of the modern agrifood industry, this section describes three fundamental typologies of supply chains and reflects on how the adoption of I4.0 technologies may help complement the strengths and address the weaknesses of each configuration.

The first configuration is the industrial commodity supply chain. This configuration focuses on the mass production of hardly differentiable products at low prices. Products are considered commodities, are highly replaceable and do not go through many processing and packaging stages. The products are also perishable making storage and handling key elements to guarantee safety and minimize losses (Aramyan et al., 2021; Vernier et al., 2021). An example is the supply chains of fresh fruit and vegetables. To successfully traverse all stages of the supply chain, the products must also comply with strict aesthetic and quality standards (van Giesen & de Hooge, 2019). As it is very difficult to differentiate products, competition is cost-based throughout the supply chain. Supply chains are highly centralized and dominated by large distribution and retail groups. These buy products from farmers and cooperatives and provide them to the end customers. Due to advantages related to economies of scale and transport optimization, distributors require growers to produce large quantities of a few varieties of products (Milford et al., 2021). The variety of products at the retail stage is guaranteed by aggregating the offer of different supply chains in the same marketplace. Producers are often small companies which lack bargaining power and act as price-takers (Morgan & Murdoch, 2000; Muller et al., 2021). Also, the commodity nature of the products makes it very difficult to raise prices. The largest share of profits is therefore absorbed by the distribution and retail groups. The scale of operation is typically large. Fast transportation allows companies to export/import products across national borders. The main goal of this type of supply chain is to minimize costs while maximizing the harvest.

Consistently, efficient resource management is particularly important for supply chains with this configuration. Referring to the application domains presented previously, it is possible to identify the most relevant I4.0 applications and technologies. These include IoT systems, AI and big data for precision agriculture applications such as determining the water needs of crops and the targeted use of natural inputs and chemical agents (Fracarolli et al., 2020; Queiroz et al., 2020). This would help farmers reduce the environmental impact of production while generating savings, in accordance with the efficiency required by this configuration.

From a managerial perspective, the main challenges to the adoption of such innovations are related to the high investment costs. Another hindrance is the management of the relations between farmers and distributors. (Lezoche et al., 2020). Distribution groups buy products mainly from small farms and retain a large share of the profits. Small agricultural businesses could face major challenges in accessing the resources for investments (Poulton et al., 2010). Furthermore, the savings generated using I4.0 technologies in the production phase could be eroded by distribution and retail groups.

In addition to resource management technologies, other opportunities relate to the adoption of technologies in the monitoring and control cluster. Solutions pertaining to the process coordination and information management domain might also provide significant advantages. IoT systems and smart sensor networks could be used to enhance product tracking and guarantee the safety of the products during the storage and transport phases. Information systems and IT software could be used to speed up the transition of products from cultivation to the retail stage, reducing losses and preventing low-quality products from reaching the market (Ingram & Maye, 2020; Lioutas et al., 2021). This could prove particularly important in this configuration, given the large volumes of otherwise undifferentiated products and the complexity of supply chains. Despite the advantages, the successful implementation of such innovations depends on the ability to manage the relationships between the actors in the supply chain, both in terms of information flows and in terms of process coordination. The power and resources imbalance between large distribution groups and small farms could severely limit the advantages offered by innovative technologies. Another obstacle concerns the need for small agricultural businesses to develop the know-how and skills to effectively use innovative technologies, a process that could significantly increase integration costs.

The second configuration is characterized by the same industrialized setup as the previous one, differing in its ability to differentiate products. This can be considered a branded industrial configuration. The differentiability of the products stems from the execution of several transformation and processing activities. These may entail product cutting, conservation or packaging (Paul et al., 2021). The uniqueness of the products is emphasized by the presence of brands and certifications on the packaging (Clark et al., 2020). Processing stages are also useful to extend products' durability. Examples are the pasta or tea supply chains. In these supply chains, the key stages are manufacturing and retailing. Manufacturers transform raw products, packaging and branding them, to differentiate them from competitors and signal their uniqueness. Transformation and labelling processes enable companies to set premium prices, and manufacturers may even be able to impose the price on distributors. Large retail groups, including supermarket chains, can contribute to product differentiation through shelf positioning or the definition of different prices for different brands. The cultivation stage can follow efficiency logic or require specific activities to provide unique qualities to the products (Gassler & Spiller, 2018; Ostfeld et al., 2019). An example of this circumstance is organic farming. As a result, competition may or may not be cost-based in the cultivation stage and is based on product differentiation in the manufacturing and later stages. The scale of operation is typically large. The products, more durable compared to the previous case, can be transported across national borders with relative ease. At the same time, the ability to generate higher margins may justify an increase in transportation costs.

Regarding the adoption of I4.0 technologies, a key role can be played by technologies in the identification and tracking cluster, including blockchain. This can be used in conjunction with identification technologies, such as RFID tags, or QR codes to pursue two objectives. First, the simplification of transactions (Bhutta & Ahmad, 2021; David et al., 2022). This type of supply chain typically involves numerous actors across different countries and generates complex products and money flows. In such a context, blockchain could prove useful to ensure reliability and transparency. It would also be possible to reassign roles and responsibilities to the actors of the supply chain (Casado-Vara et al., 2018; Kamilaris et al., 2019). Additionally, it would also be possible to certify products' origin and properties, enabling the execution of differentiation strategies. Additionally, it would also be easier for certified products to access markets characterized by stricter standards. (Busse & Siebert, 2018; Soon & Wallace, 2018). As for the barriers to the adoption of advanced tracking solutions, the main obstacle relates to the need to equip all the players in the supply chain with the necessary technologies. Indeed, tracking systems may require substantial investments and might entail the need to develop new technological and organizational capabilities (Ingram & Maye, 2020; Nawandar & Satpute, 2019). Other challenges are the definition of contractual agreements and the development of coordination mechanisms between the players in the supply chain (Camilleri 2019). Some challenges also concern the limitations of currently available blockchain tracking systems. These include throughput, latency and scalability issues, among others (Casino et al., 2019; Zhao et al., 2019). Finally, some authors highlight the lack of shared policies and privacy concerns (Kamilaris et al., 2019; Malisic et al., 2023).

Alternative food networks (AFNs), also known as short food supply chains, are explicitly designed to differ from the traditional industrial model. These represent an attempt to address some of the more controversial elements of highly industrialized food production systems. Indeed, the emergence of AFNs is a relatively new phenomenon and the subject of a rapidly increasing number of studies. It is necessary to stress how the expression AFNs does not indicate a unique type of agrifood supply chain but includes a multiplicity of configurations united by similar objectives and design philosophies. According to several studies (Cruz et al., 2021; El Bilali et al., 2021; Rosol & Barbosa, 2021), the rise of AFNs can be traced back to two main reasons. On the demand side scepticism of a significant share of consumers towards traditional industrial systems, which are perceived as unsustainable and not trustworthy (Gunarathne et al., 2018; Krzyzanowski Guerra et al., 2021). On the supply side, a key element is small producers' desire to experiment with alternative supply chain configurations, reducing the ability of large distribution and retail groups to dictate prices while absorbing the largest profit shares (Van Der Ploeg et al., 2017). AFNs try to satisfy these needs by focusing attention on two main dimensions: the redesign of supply chains and the focus on products' qualities. In terms of supply chain configuration, AFNs aim to reduce the distance, both physical and conceptual, between producers and consumers. These supply chains involve fewer levels between the cultivation and the retail stages, with the prevalence of direct or local marketing activities (Milford et al., 2021). In these instances, small producers, often located near urban centres, may transport and sell their products directly to consumers or Ho.Re.Ca. businesses. Alternatives are community-supported agriculture (CSA) initiatives, in which consumers invest resources in the supply chain to gain direct access to products (Rosol & Barbosa, 2021; Sacchi et al., 2022). The absence of a central intermediary level limits the scalability of such initiatives but allows consumers to access fresh products and enables growers to benefit from higher margins. Despite the prevalence of direct and local marketing activities, it is sometimes possible to observe the presence of actors acting as mediators. This role can be played by producer associations or third-party companies and serves to connect supply and demand to increase the scale of operations (Rosol & Barbosa, 2021). As for the focus on quality, AFNs leverage the proximity between the places of production and consumption to offer fresh and seasonal products, often emphasizing the importance of the origin and traditional cultivation methods (Riefler, 2020; Soon & Wallace, 2018). These features can be exploited to differentiate products and gain an advantage over similar products offered by large-scale retailers. At the same time, due to their distinctive characteristics, the scale of operations is typically limited, production volumes are low, and the variety of offerings depends on the seasonality of products. Furthermore, these configurations struggle to exploit economies of scale and leverage large investments.

Regarding the adoption of I4.0 technologies, solutions from two technological clusters could be effectively implemented. As for monitoring and control technologies, IoT systems, sensor networks and UAVs can be employed to monitor parameters concerning soil properties, plant growth, and weather conditions. This can in turn enhance farmers' ability to grow quality products without resorting to intense resource consumption (Mahroof et al., 2021; Tsouros et al., 2019). Again, the main barriers are represented by the high investment costs and the need to develop the required know-how. Indeed, even though rapid technological advances dramatically reduced the cost of sensors, software and devices, companies must consider the expenses needed to manage, maintain and develop the capabilities required to successfully integrate technologies into the business. As for process coordination and information management technologies, the use of farm management information systems and big data would allow small businesses to manage operations in an integrated way. Information can also be used to gain a comprehensive understanding of products' flows and activities (Mazzetto et al., 2020; Wolfert et al., 2017). Given the lack of intermediation that characterizes AFNs, leveraging the advantages of integrated management and information systems could simplify product management and demand forecasting. The main obstacle is represented by the difficulty to choose among available solutions, and the need to reconcile innovative technologies with traditional business practices.

Figure 1.4 offers a representation of the three different types of agrifood supply chains. It also shows the technologies most suited for each type of supply chain with an indication of their utilization at different stages.

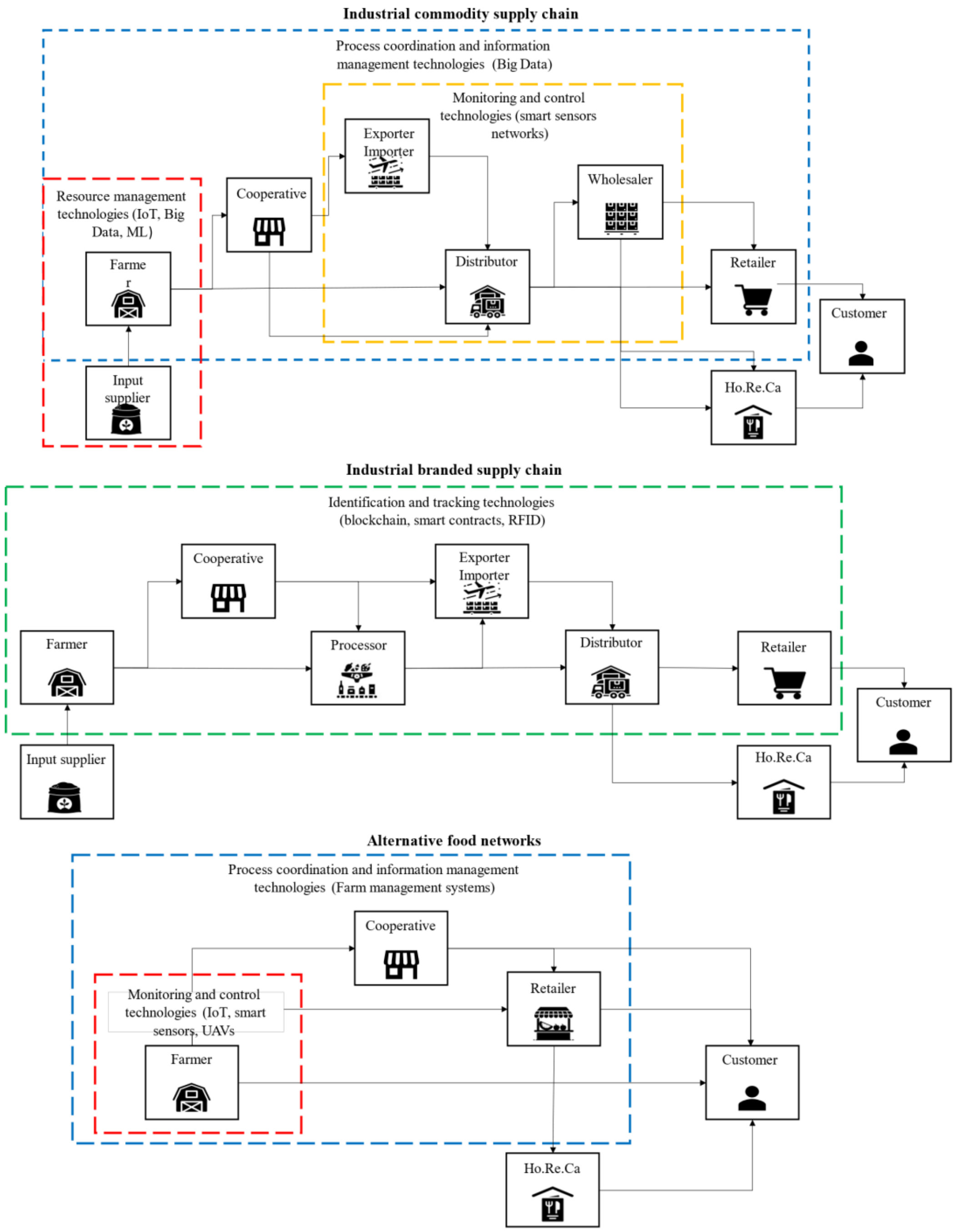


Figure 1.4 types of agrifood supply chains and an indication of I4.0 technologies utilization.

1.6 Conclusions and research directions

The modern agrifood industry is called to address long-standing sustainability and economic challenges. Institutions and consumers require agrifood companies to reduce the environmental impact of production and enhance the transparency and accountability of supply chains while remaining economically sustainable. Recent literature suggests that the adoption of innovative

I4.0 technologies represents an opportunity for agrifood companies to innovate processes and develop more sustainable business models. However, despite the growing interest in the sustainable technological development of the agrifood industry, some key aspects remain under-investigated. Although several studies review the applications of innovative technologies in the agrifood industry, most focus primarily on the implications in terms of environmental sustainability. These investigate how I4.0 technologies may help agrifood companies optimize the consumption of natural resources and limit emissions and the use of chemical agents (Amentae & Gebresenbet, 2021; Maffezzoli et al., 2022). Other studies focus on the design of innovative technological solutions for the execution of specific activities (Goap et al., 2018; Muangprathub et al., 2019). From this perspective, the literature fails to adequately consider the organizational and managerial implications of the adoption of I4.0 technologies. Indeed, the investigation of the interplay between technological innovation, objectives and characteristics of agrifood supply chains is still in its nascent stage.

This study helps bridge this gap by classifying I4.0 technologies based on applications in the agrifood industry, and by providing a framework analysing how I4.0 may complement the characteristics and goals of different types of agrifood supply chains. To this end, the evolution of the agrifood industry is analysed, to identify its main characteristics and dynamics. Next, the chapter provides a review of technological applications leading to the identification of four main clusters, namely monitoring and control, resource management, product tracking, and information management. Rather than focusing on the technical aspects and the implementation of single solutions, clusters group together the technologies used for the same purpose. Furthermore, the chapters present a reflection on how I4.0 technologies may help different types of agrifood supply chains achieve sustainability and economic goals. Specifically, three types of supply chains are identified, characterized by different objectives and dynamics. The most relevant technological solutions for each type of supply chain are presented, and applications, benefits and challenges are discussed.

Results suggest that industrial supply chains supplying perishable and non-differentiable products should focus on technologies capable of reducing resource consumption and generating savings. They should also adopt monitoring and control technologies to guarantee product quality and reduce waste. Industrial supply chains that offer durable products and look to differentiate their offer from competitors can leverage blockchain and identification technologies to emphasize the unique qualities of the products and enhance brand identity. Finally, alternative food networks can take advantage of coordination technologies and

decision-making support software to streamline processes and simplify supply chain management.
In terms of theoretical implications, this study provides two main contributions. First, it offers a novel classification of I.40 technology applications in the agrifood industry, identifying four main clusters. This is useful to understand how I4.0 technologies may impact the performance and sustainability of agrifood companies. Second, the study provides a framework that highlights significant differences between the three fundamental typologies of agrifood supply chains. This enables a reflection on how the adoption of innovative technologies might affect different typologies of agrifood companies. Furthermore, this invites consideration of key managerial aspects in the analysis of technological innovation in the agrifood industry.
As for practical implications, the results suggest that to benefit from the adoption of I4.0 technologies two considerations are essential. First, technologies need to be aligned with supply chain objectives and characteristics. Management must first define the objectives to achieve and then identify the technologies that can provide the greatest benefits. Second, the study shows that the same technologies can provide multiple advantages, depending on three main conditions. On the one hand, management must consider the synergies of the integration of multiple technologies. On the other, it is necessary to gain a clear understanding of the requirements, know-how and capabilities needed to effectively use the technologies. Finally, roles, responsibilities, and coordination mechanisms with the other players in the supply chain must be carefully defined.
Despite its contributions, this study is not exempt from limitations. First, this study only considers applications in the cultivation and production stages of fruit and vegetable supply chains. Future research could focus on different agrifood sectors, highlighting similarities and differences. Also, future investigations could analyse the benefits provided by the adoption of innovative technologies in other stages of agrifood supply chains. Furthermore, the study did not consider all available technologies and solutions. This was impractical due to the high number and seamless emergence of new solutions. In this regard, the exclusion of the keyword "digitalization" and related terms from the search string is a notable limitation. While this approach allowed for a more targeted examination of Industry 4.0 technology applications in the agrifood sector, it also restricted the scope of the analysis, potentially overlooking studies that address the intersection of digital transformation and sustainability. Future research could address this gap by leveraging AI tools to conduct an extensive and systematic review of the literature. Furthermore, future research could focus on providing frameworks to evaluate and

compare multiple technologies for relevant applications. Key elements to analyse include system design, requirements, and management mechanisms.

Finally, this qualitative, conceptual study does not address some key gaps in the scientific literature on sustainable technological development of the agrifood industry. Specifically, the review of the literature highlighted a severe lack of empirical studies, aimed at assessing the impact of I4.0 technologies on the sustainability and economic performance of agrifood companies. This is crucial to provide evidence of the key role that innovative technologies may play in supporting the sustainable transition of the agrifood industry while identifying limits and unintended consequences. On this note, a particularly relevant gap concerns the lack of studies focusing on the impact of I4.0 technologies on the social sustainability of agrifood companies. Lastly, several organizational and managerial issues related to the effective adoption of I4.0 technologies in the agrifood industry remain under investigation.

Thus, the studies presented in the following chapters aim to help address the literature gaps highlighted by this review. Specifically, chapter two focuses on assessing the impact of I4.0 technologies on the social sustainability of agrifood companies. Considering once again the cultivation and production activities, the study proposes a novel theoretical model for assessing the social impact of adopting I4.0 technologies in the agrifood industry. In this, the chapter delves into key social issues affecting the agrifood industry and provides and in-depth analysis of the challenges and opportunities that technological innovation may provide to agrifood companies in terms of social sustainability. Furthermore, after identifying suitable metrics, chapter two presents the results of an empirical investigation aimed at validating the model and assessing the real impact of I4.0 technologies on the social sustainability of agrifood companies.

Next, chapters three and four address another fundamental gap in the literature, introducing essential organizational and managerial issues into the discussion on the adoption of I4.0 technologies in the agrifood industry. To this end, the chapters focus on the adoption of blockchain tracking systems in wine supply chains. This is a particularly relevant scenario, as product tracking is essential to ensure accountability and support wineries address serious fraud and communication issues affecting the industry. Furthermore, this provides the opportunity to investigate how the adoption of innovative technologies can help agrifood companies reconcile economic and social sustainability objectives.

CHAPTER II – Impact of Industry 4.0 technologies on the social sustainability of agrifood companies

Summary

This chapter aims to address one of the key gaps identified in the literature review of the preceding chapter. Specifically, this investigation moves from the observation that the connection between the adoption of I4.0 technologies and the social sustainability of agrifood companies has so far been underexplored. This gap is significant given the relevance of the social issues affecting the agrifood sector and the potential impact that technological innovation may have on key aspects of social sustainability. Indeed, while some scholars highlight the positive effects of introducing innovative technologies, others point to possible unintended consequences. This debate is also exacerbated by the lack of appropriate measures and indicators to assess the effects of technological innovation on the social sustainability of agrifood companies. To help bridge this gap, this chapter develops a robust theoretical model to analyse the effects of I4.0 technologies on three essential aspects of social sustainability in the agrifood industry. The social sustainability dimensions are modelled by referring to the stakeholders' theory and the concept of Corporate Social Responsibility (CSR), leading to the identification of sustainability metrics related to labour management, supply chain management, and stakeholder relationships. To assess companies' ability to leverage Industry 4.0 technologies to achieve sustainability objectives, the model incorporates the concept of technological capability, distinguishing between technological strategy, maturity, and skills. The chapter also provides model validation through a survey conducted among 116 Italian agrifood SMEs, and the use of the Structural Equation Modelling (SEM) methodology. The results highlight the complexity of the relationship between technological innovation and social sustainability goals, enabling crucial reflections on the social implications of adopting I4.0 technologies in the agrifood industry. This chapter is adapted from an article published in 2024 in the Business Strategy and Environment journal (Cricelli et al., 2024).

2.1 Introduction

As discussed in the previous chapter, the adoption of Industry 4.0 technologies is driving innovation in the agrifood industry, leading to the definition of the Agriculture 4.0 paradigm. This represents a new approach to farm management, based on the use of real-time data and precision agriculture techniques (Maffezzoli et al., 2022; Sott et al., 2020). Over the years, this topic attracted considerable scientific interest, initiating the investigation of the implications of the adoption of I4.0 technologies in the agrifood industry (Bongomin et al., 2020; Lezoche et al., 2020). Scholars highlight how the adoption of I4.0 technologies presents agrifood companies with the opportunity to reconcile economic goals with sustainability. From this perspective, multiple studies focus on the connection between environmental and economic sustainability (Bandinelli et al., 2020; Clapp & Ruder, 2020; Forney & Epiney, 2022; Tang & Yang, 2016; Xie et al., 2022). These studies show how by using real-time and site-specific data, I4.0 technologies help agrifood companies improve resource management, productivity and efficiency. A growing research stream focuses on the impact of I4.0 technologies on the sustainability of agrifood companies. This has its theoretical foundations in the well-known Triple Bottom Line (TBL) framework, which considers environmental, economic and social sustainability aspects equally (Elkington, 1998).

However, while the environmental and economic benefits provided by I4.0 technologies are widely recognized, their impact on the social sustainability of agrifood companies is currently under-investigated. Several chapters review I4.0 technological applications, offering a conceptual analysis of how technologies are set to disrupt the agrifood industry along the three dimensions of sustainability (dos Reis et al., 2020; Hassoun et al., 2022; Latino et al., 2023; Lezoche et al., 2020; Morella et al., 2021; Senturk et al., 2023). While providing valuable contributions, these studies do not focus precisely on social sustainability issues and offer a mainly theoretical contribution.

On a different note, some studies focus on the design and evaluation of technological solutions for specific agrifood applications (Mavridou et al., 2019; Shockley et al., 2019; Wolfert et al., 2017). Besides offering a thorough analysis of the potential of technologies, these chapters typically focus on assessing system performance and overlook the social implications of technological innovation in the agrifood industry.

Moreover, the few studies focusing on investigating how I4.0 technologies affect the social sustainability of agrifood companies return a complex picture. One of the fundamental aspects of social sustainability in organizations concerns the quality of the working environment and the management of human resources. From this perspective, the prevailing idea in the literature is that the adoption of I4.0 technologies could help agrifood companies create safer and healthier working environments (Alves et al., 2023; Monteleone et al., 2020; Nawandar & Satpute, 2019). Multiple studies show how the dependence on uncontrollable environmental factors subjects agricultural workers to harsh working conditions (Martin et al., 2022; Rose et al., 2021). The use of I4.0 technologies enables the automation of the most physically demanding tasks, reducing operator workloads and increasing workplace security (Giannoccaro et al., 2020; Lioutas et al., 2021). However, some empirical studies present conflicting evidence. Weber et al. (2022) and Prause (2021) explain that the adoption of I4.0 technologies creates new forms of labour control, allowing farm owners to put pressure on workers to increase productivity. Furthermore, while some scholars argue that the adoption of I4.0 technologies favours the development of new skills and the definition of new roles in agrifood companies (Martin et al., 2022; Neumann et al., 2021), others argue that the lack of technological skills is one of the main barriers to the adoption of I4.0 technologies in the agrifood industry and entails the risk of marginalizing workers with more traditional skills (Abbasi et al., 2022; Derakhti et al., 2023).

Beyond issues relating to labour management, several studies highlight how the development of global supply chains and the emergence of food scandals endangering consumers' health raised serious concerns regarding the security and accountability of agrifood supply chains (Milford et al., 2021; Smith & McElwee, 2020). The combination of modern ICTs and I4.0 technologies such as blockchain and IoT provides businesses with the opportunity to ensure transparency and respect for sustainability standards throughout the supply chain. This could also bring significant social benefits, improving relationships between supply chain partners and external stakeholders, including governments and consumers (Finger, 2023; S. Mukherjee et al., 2021; Vernier et al., 2021).

Despite this, relevant studies suggest that the effective use of I4.0 technologies requires an active commitment by companies (Brookbanks & Parry, 2022; Morella et al., 2021). In this scenario, the technological capability of the company plays a pivotal role. To derive social benefits from technological innovation, agrifood companies must ensure that they develop the necessary skills and integrate I4.0 technologies into their business activities effectively (Abbasi et al., 2022; Gaspar et al., 2021; Zeng & Lu, 2021). Unfortunately, most of the literature on technological innovation in the agrifood industry failed to empirically investigate the connection between technological capability and the impact of I4.0 technologies on companies' social sustainability (Latino et al., 2023). This study aims to address this knowledge gap by answering the following research question:

RQ3) How does the use of I4.0 technologies affect the social sustainability of agrifood companies?

To answer the research question, we first analyse the available literature to identify metrics and indicators that explain how agrifood companies can use I4.0 technologies to address key social sustainability issues. To model how firms acquire and integrate technologies into their business, we use the concept of technological capability (Annarelli et al., 2021; Arballo et al., 2019; Uddin et al., 2023; Wang et al., 2006). Specifically, we identify three key capabilities that the company must develop to effectively integrate I4.0 technologies into the business, related to the development of I4.0 technological skills, the definition of an I4.0 technological strategy and the I4.0 technological maturity of the firm.

Then, we draw from the literature on companies' CSR and supply chain social responsibility to identify the main issues in the agrifood industry, distinguishing between different aspects of social sustainability that involve multiple stakeholders throughout the supply chain (Lu et al., 2012; Mani et al., 2020; Pfajfar et al., 2022; Uddin et al., 2023). Specifically, we focus on the management of human resources, communication with supply chain partners and relationships with consumers and society. Finally, we use data from a survey aimed at 1.320 Italian agrifood industry companies to validate a structural equation model designed to assess the impact of I4.0 technologies on the social sustainability of agrifood companies.

Overall, this study provides two main theoretical contributions. First, it offers empirical evidence of the impact of I4.0 technologies on the social sustainability of agrifood companies. Second, it examines how the adoption of I4.0 technologies influences the social sustain ability of agrifood companies. This advances the literature by explaining how technological innovation impacts social sustainability in the agrifood industry and by enabling the definition of a framework to assess the social impact of I4.0 technologies. This study also presents notable practical implications, which can help the management of agrifood companies reap the social benefits of adopting I4.0 technologies. The chapter is organized as follows. The second section provides the theoretical background of the study, with an overview of how I4.0 technologies may impact social sustainability in the agrifood industry.

Then, we develop our hypotheses and build the models. In this, we also present the main theories we used to model the concepts of I4.0 technological capability and social sustainability in the agrifood industry. In the next section, we describe the methodology, then we present the results. In the last two sections, we discuss the results and conclude, respectively.

2.2 Theoretical background

The concept of Agriculture 4.0 entails a new paradigm in which I4.0 technologies are seamlessly integrated into agricultural practices. Over the years, multiple studies reviewed the applications of I4.0 technologies in the agrifood industry (Abbasi et al., 2022; J. Miranda et al., 2019; Sott et al., 2020). Prominent technologies include IoT, Big Data, Artificial Intelligence, and blockchain (Candiago et al., 2015; dos Reis et al., 2020; Lezoche et al., 2020; Wolfert et al., 2017). In this, the adoption of I4.0 technologies offers agrifood companies the opportunity to promote the conscious use of resources, while increasing productivity and efficiency. Indeed, most of the literature on the impact of I4.0 technologies in the agrifood industry stresses the relationship between environmental and economic sustainability (Annosi et al., 2020; Khanna et al., 2022; Luzzani et al., 2021; Ruiz-Garcia & Lunadei, 2011). Yadav et al. (2022) identify five main research areas, i.e. food safety, information management, food waste, control and monitoring, decision-making and miscellaneous applications. Furthermore, in their systematic review of the literature on Agriculture 4.0, Maffezzoli et al. (2022) highlight how application domains include water management, crop management, prediction of climate conditions and soil monitoring.

However, while the economic and environmental benefits guaranteed by I4.0 technologies are well documented, the social implications of technological innovation are currently under investigated. Recent studies suggest that the adoption of I4.0 technologies in the agrifood industry may have significant social implications, in terms of human resource management, security and accountability of supply chains, and impact on society (Janker & Mann, 2020; Luzzani et al., 2021; Rijswijk et al., 2021).

The peculiar working conditions and the dependence on uncontrollable natural factors entail unique challenges relating to labour management. Many activities and field operations can only be executed when specific environmental conditions are met. This implies that during critical periods, such as sowing or harvesting, farmers have to contend with work overload, lack of breaks and days off, and a general deterioration of working conditions (Weber et al., 2022). Also, during these periods, many companies rely heavily on temporary employment contracts, hiring workers who may suffer harsh working conditions (Christiaensen et al., 2021; Janker & Mann, 2020). The adoption of I4.0 technologies presents an opportunity to mitigate these negative effects. Real-time analysis of environmental conditions allows for better planning of activities and better management of human resources. Furthermore, the use of smart IoT systems for continuous crop monitoring enables companies to reduce human interventions and alleviate workloads. Finally, the automation of the most physically demanding tasks can help reduce the pressure on field operators and contribute to the creation of safer work environments (Hrustek, 2020; Lioutas et al., 2021).

At the same time, recent studies warn about the potential unintended consequences of technology development. Prause (2021) analyses the implications of digitalization on the social sustainability of agrifood labour, with mixed evidence. Results suggest that technologies assist farm owners in acquiring technological and managerial skills and improve activity planning. In some instances, however, field operators lamented a significant increase in workloads. By enabling real-time monitoring of the pace of activities in the fields, smart technologies allow owners to exert pressure on the workers, who are pushed to increase productivity. Furthermore, the authors question whether rapid technological innovation can lead to job losses and the marginalization of workers with low technological skills. From this perspective, several studies find that one of the main challenges to the diffusion of I4.0 technologies in industry agrifood is the lack of technological skills and an innovation-oriented strategy (Derakhti et al., 2023; Kamble et al., 2020). Mahdad et al. (2022) show how farmers' unfamiliarity with technologies generates scepticism and resistance among workers. Several studies emphasize the importance of top management in the definition of a technological strategy (Ghobakhloo et al., 2023; Rijswijk et al., 2021). Thus, the development of the company's technological capability is key to enabling innovation in agrifood companies.

Observing the issue from a broader perspective, scholars generally agree that the adoption of I4.0 technologies can significantly affect the relationships among partners in agrifood supply chains. This may have notable implications from a social sustainability standpoint (Clapp & Ruder, 2020; Glavee-Geo et al., 2022). Mahdad et al. (2022) observe how modern information technologies can improve information sharing and strengthen interdependencies between actors in agrifood supply chains. Indeed, many successful applications of I4.0 technologies in the agrifood industry stem from the collaboration between agrifood companies and external technology providers (Brookbanks & Parry, 2022; Motta et al., 2020). This can help agrifood companies circumvent skill gaps and develop their technological capability, eliciting collaboration and a more equitable distribution of value (Glavee-Geo et al., 2022; Muller et al., 2021). Furthermore, by increasing transparency and promoting communication between partners, I4.0 technologies can help agrifood companies disseminate sustainability standards throughout the supply chain (León-Bravo et al., 2017; Mani et al., 2018; Sharma et al., 2022). This can lead to significant environmental and social benefits, as companies can select reliable partners, and ensure compliance with ethical standards regarding sourcing, production processes, and product quality.

Going beyond the boundaries of the supply chain, it is important to emphasize the social responsibilities of the agrifood industry towards society. From this perspective, key issues are the control and accountability of agrifood supply chains. Ensuring product safety is not only mandatory to access markets and comply with regulations but is also key to providing consumers with reliable information (Dos Santos et al., 2021; Majdalawieh et al., 2021; Rao et al., 2021). Brooks et al. (2021) highlight how the emergence of security issues and fraudulent practices undermined consumers' trust in agrifood supply chains. As a result, consumers place greater emphasis on product authenticity (Menon & Jain, 2021). Furthermore, governments and national authorities exert pressure on agrifood supply chains by enacting stricter regulations (Swinnen et al., 2021), and standards are used to reduce information asymmetries throughout agrifood supply chains. As for the role that I4.0 technologies can play, recent studies analyse how the adoption of IoT systems and blockchain technology allows companies to track products "from farm to fork". This can help create safer and more transparent supply chains (David et al., 2022; Rana et al., 2021; Senturk et al., 2023). Also, the adoption of effective traceability systems can shield consumers and producers from fraud and counterfeiting. However, the lack of technological skills and companies' limited awareness seem to hinder the adoption of advanced tracking solutions in the agrifood industry (Corallo et al., 2020; Galati et al., 2021).

Overall, the contribution that I4.0 technologies can provide to the social sustainability of agrifood businesses is currently little investigated. Several authors, including Costa et al. (2023) and Maffezzoli et al. (2022) highlight the need for quantitative studies to investigate the impact of innovative technologies on the social sustainability of agrifood companies. The authors emphasize the need to identify reliable measures to assess how I4.0 technologies affect the multifaceted dimensions of social sustainability within the agrifood industry. Finally, considering the potential of I4.0 technologies to support socially sustainable innovation in the agrifood industry, it is important to analyse how the development of companies' technological capability influences the achievement of social sustainability objectives both within and outside the firm.

2.3 Hypothesis development

This chapter aims to assess how the adoption of I4.0 technologies impacts the social sustainability of agrifood companies. The next paragraphs illustrate the hypotheses underlying the study. To model how companies can effectively integrate I4.0 technologies into business activities we use the concept of technological capability. Also, we refer to the literature on CSR companies to identify the main social benefits that I4.0 technologies may provide to agrifood companies.

2.3.1 Technological capability

The concept of technological capability is widely used by scholars to analyse the problem of technology management in organizations (Annarelli et al., 2021; Arballo et al., 2019; Keinz & Marhold, 2021; Valdez-Juárez & Castillo-Vergara, 2021; M. Xu & Tao, 2024). As shown by Coombs & Bierly (2006) and Wang et al. (2006), the concept of technological capability has its roots in the resource-based view (RBV), in the theory of dynamic capabilities and the knowledge-based view (KBV) of the firm. Following the RBV, companies' main source of competitive advantages is the ability to leverage unique, distinctive and difficult-to-imitate resources (Barney, 1991). Accordingly, Altuntas (2023) highlights how a firm's technological capability is intrinsically linked to the definition of a technological strategy, through which the management plans investments, processes, and organizational changes so that the company can take advantage of the technologies to drive innovation efforts. Consistently, Taghizadeh et al. (2020) demonstrate how SMEs' performance in open innovation initiatives is influenced by technological capability, which goes far beyond the use of technologies and implies a strong strategic orientation towards innovation and R&D activities.

The theory of dynamic capabilities posits that to sustain a competitive advantage, companies must develop the ability to analyse the external environment, seize opportunities, and reconfigure (Teece et al., 1997). Thus, the concept of technological capability takes on a dynamic quality, related to the company's ability to effectively integrate technologies into business processes, and develop technological maturity. Al-Mamary et al. (2022) identify four fundamental aspects of technological capability, encompassing the ability to integrate the technologies into business processes, to use technologies to improve products, and the ability to upgrade technologies.

The KBV theory suggests how firms require adequate knowledge management systems to benefit from resources and create a competitive advantage (Grant, 1996). Given the importance of technological assets for companies in modern industries, it naturally follows that knowledge management plays a crucial role in assessing the organization's technological capability. Drawing on the classic distinction between explicit and tacit knowledge, Peerally et al. (2022) and Lin & Lai (2021) highlight the role of human resources in developing the technological capability of the firm. Thus, a comprehensive evaluation of technological capability requires considering the company's ability to develop employees' technological skills. In this chapter we ground our understanding of a company's technological capability on the above-mentioned theories, distinguishing three key aspects related to the definition of an I4.0 technological strategy, the development of I4.0 technological skills, and the assessment of the level of I4.0 technological maturity of the firm, respectively. Then, we use the concept of technological capability to assess how the adoption of I4.0 technologies affects social sustainability in agrifood companies.

2.3.2 Social sustainability

Given the lack of established metrics to evaluate social sustainability in the agrifood industry, we draw from the literature on Corporate Social Responsibility and stakeholders' theory to investigate its multiple facets. We moved from the popular definition provided by the Brundtland Commission (1987), which describes sustainable development as the "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*", encompassing social equity, inclusion, participation, cohesion, and resilience. Then, we focus on defining social sustainability for business. To this end, we refer to the well-established concept of CSR, which originated from Carroll's seminal work on the economic, legal, ethical and discretionary responsibilities of companies (Carroll, 1979). Indeed, companies' social responsibilities extend beyond the firm's boundaries, affecting the relationships with supply chain partners, communities and the environment in which it operates (Esposito & Ricci, 2021; Fatima & Elbanna, 2023; Mani et al., 2016). Thus, following the main theoretical developments, we ground the concept of social sustainability for agrifood companies on CSR, sustainable supply chain management and the stakeholders' theory (Al-Shammari et al., 2022; ElAlfy et al., 2020; López-Concepción et al., 2022; Mani et al., 2018; Mosca & Civera, 2020; Pfajfar et al., 2022; Waheed & Zhang, 2022). Specifically, we identify three fundamental dimensions of business social sustainability, pertaining to sustainable supply chain management, responsibilities to society and external stakeholders, and human resources management, and discuss how the development of the firm's technological capability associated with the adoption of I4.0 technologies might affect each.

2.3.3 Sustainable supply chain management

We start with the analysis of sustainability at the supply chain level, referring to the well-established literature on sustainable supply chain management (Carter et al., 2020; Fernando et al., 2022; Marshall et al., 2015; Uddin et al., 2023). This requires companies to focus not only on internal sustainability targets but also to transfer their sustainability standards to supply chain partners. This entails supporting partners' initiatives and ensuring that partners implement sustainability practices throughout the supply chain (Dubey et al., 2019; Ebinger & Omondi, 2020). While most studies consider environmental and social sustainability aspects together, Marshall et al. (2015) observe that in practice, companies tend to treat these two concepts distinctly, sometimes making trade-offs between environmental and social sustainability initiatives. This can be a particularly serious concern for agrifood companies, which are pressured to reduce the environmental impact of cultivation (Borsellino et al., 2020; El Bilali et al., 2021), but are also affected by serious issues regarding labour management and supply chain accountability. By adopting modern information systems, agrifood companies may be able to make their business models more socially sustainable, improving information sharing and coordination among supply chain partners. Additionally, I4.0 technologies could help businesses to better monitor the supply chain, allowing them to effectively implement CSR initiatives and build trust relationships with partners. Consequently, I4.0 technological capabilities are essential for businesses to effectively enhance supply chain social sustainability. Thus, we aim to test the following hypothesis:

H1.a) I4.0 technological skills positively influence the social sustainability of agrifood companies in terms of supply chain management.

H1.b) I4.0 technological strategy positively influences the social sustainability of agrifood companies in terms of supply chain management.

H1.c) I4.0 technological maturity positively influences the social sustainability of agrifood companies in terms of supply chain management.

2.3.4 Sustainable stakeholders' management

Agrifood companies have the responsibility to ensure the quality of production processes and product safety. Despite this, the occurrence of food scandals repeatedly endangered consumer health and undermined trust in agrifood supply chains (Chandan et al., 2023; Smith & McElwee, 2020). Furthermore, the prevalence of fraud and counterfeiting poses serious concerns regarding firms' accountability and supply chain transparency (Adamashvili et al., 2021; Dos Santos et al., 2021; Ebinger & Omondi, 2020). In recent years, agrifood companies shifted their focus towards implementing more ethical production practices to regain consumer trust and comply with regulations (Bandinelli et al., 2020; Majdalawieh et al., 2021). International standards have also been developed to help consumers make informed decisions (Dos Santos et al., 2021; Muller et al., 2021; Ostfeld et al., 2019). However, certifications and regulations have shown weaknesses, and agrifood companies require new tools to substantiate their claims. The development of advanced product tracking systems based on the combination of I4.0 technologies such as blockchain and IoT offers companies the opportunity to prove their commitment to environmental and social sustainability. Furthermore, the use of such technologies could improve the transparency and security of supply chains, enabling agrifood companies to build relationships of trust with consumers and governments. The literature suggests, however, that integrating these solutions into business processes requires advanced I4.0 technological capabilities and developing the skills and maturity necessary to adapt the management of information and business processes. Therefore, we aim to test the following hypothesis:

H2.a) I4.0 technological skills positively influence the social sustainability of agrifood companies in terms of stakeholders' management.

H2.b) I4.0 technological strategy positively influences the social sustainability of agrifood companies in terms of stakeholders' management.

H2.c) I4.0 technological maturity positively influences the social sustainability of agrifood companies in terms of stakeholders' management.

2.3.5 Sustainable human resources management

An essential aspect of social sustainability in businesses is the organization of work and the management of human resources (Gàlvez et al., 2020; Grybauskas et al., 2022). Companies must guarantee the health, safety, and well-being of workers. Additionally, firms must ensure fair wages and balanced workloads. Furthermore, companies must take into account the needs of the employees, supporting their training and professional growth (Amrutha & Geetha, 2020;

Pinzone et al., 2020). From this perspective, agrifood companies present unique challenges. Dependence on uncontrollable environmental factors affects labour management, negatively affecting human resources. Agrifood workers face cyclical work peaks and may operate in harsh environmental conditions for prolonged periods. Furthermore, cultivation activities require the execution of repetitive and physically demanding tasks, which negatively impact workloads and operators' health. Thus, responsible labour management is a key aspect of the social sustainability of agrifood companies, which includes organizational issues alongside important aspects related to workers' conditions and the quality of the working environment. The adoption of I4.0 technologies and the development of I4.0 technological capability could help mitigate the effects of unpredictable factors, reduce work overloads and help agrifood companies create safer and healthier work environments. For example, automation can be used to support and alleviate the workload of field operators. Additionally, predictive models can be used to improve activity planning and reduce the impact of environmental factors on labour management. Finally, the adoption of I4.0 technologies could lead to the empowerment of workers, who may develop new managerial and high-level skills (Martin et al., 2022; Neumann et al., 2021). Thus, we aim to test the following hypothesis:

H3.a) I4.0 technological skills positively influence the social sustainability of agrifood companies in terms of human resources management.

H3.b) I4.0 technological strategy positively influences the social sustainability of agrifood companies in terms of human resources management.

H3.c) I4.0 technological maturity positively influences the social sustainability of agrifood companies in terms of human resources management.

Figure 2.1 illustrates the model underlying the hypotheses. The development of firms' technological capability resulting from the adoption of I4.0 technologies is assessed by distinguishing between technological skills, maturity, and strategy. It influences the ability of companies to leverage innovative technologies to improve essential aspects of social sustainability. In turn, this is evaluated through key metrics sustainable labour management, sustainable supply chain management, and sustainable stakeholder management metrics.

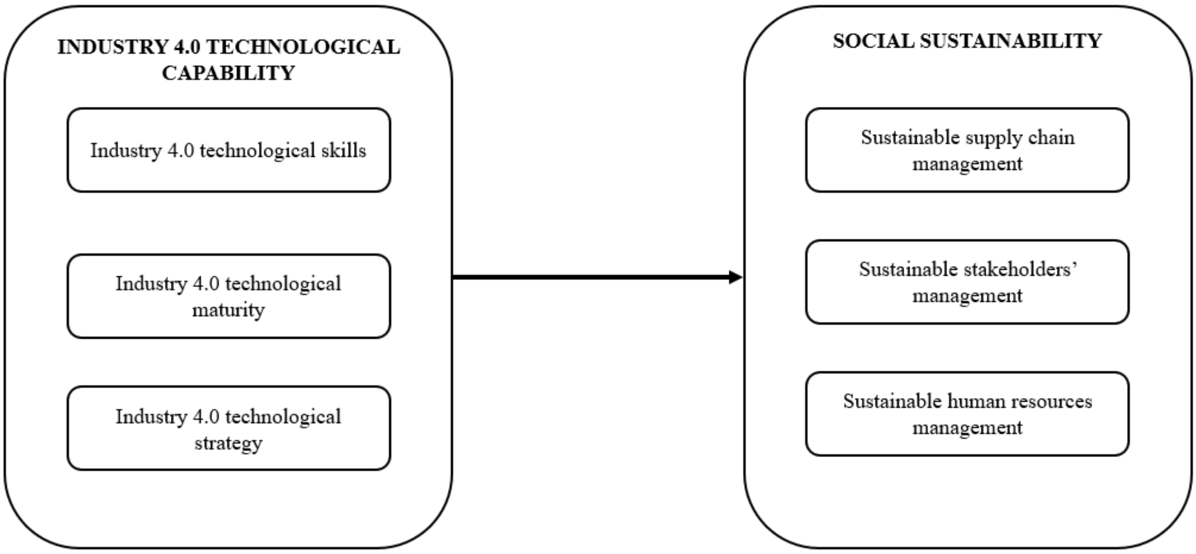


Figure 1.1 theoretical model.

2.4 Methodology

To assess the impact of Industry 4.0 technologies on the social sustainability of agrifood companies, we adopted a quantitative approach based on the analysis of data obtained from a survey aimed at Italian agrifood companies. The following sections provide a detailed overview of the data collection process, survey structure, and data analysis techniques.

2.4.1 Data collection and sampling

The data were collected between December 2023 and February 2024 through a survey targeting 1.320 Italian agrifood companies. We chose to focus on Italian companies for two reasons. First, the Italian agrifood industry is characterized by the quality and variety of its products, as well as intense international trade. By focusing on companies supplying different categories of agricultural products, we are able to enhance the generalizability of the results, which relate well to all firms performing cultivation activities, regardless of the crop typology. Second, Italy is a highly industrialized country, which is a favourable condition to assess the impact of I4.0 technologies on agrifood production. The survey is based on a questionnaire that we pre-tested on a small sample of agrifood firms. The results of the pre-test allowed us to assess the completion time and the clarity of the questionnaire, implementing small improvements in the wording and presentation of the questions.

We carefully selected companies to meet two criteria. First, we focused on agrifood companies involved in the cultivation, harvesting, and preparation of agrifood products for processing. We

also included companies engaged in processing activities, provided they also carried out cultivation activities. We excluded firms that only perform processing activities, as a key goal of the study was to evaluate the impact of I4.0 technologies on the social sustainability of cultivation-related activities, encompassing field operations and labour management. We also excluded companies in the meat industry. Although the literature suggests that I4.0 technologies can have a significant impact on livestock activities, these pose unique social sustainability issues, such as those related to animal conditions, which fall outside the scope of this study.
Regarding the second criterion, we chose to include only companies with a revenue exceeding €500.000. Thus, we excluded small-scale businesses, as they are less likely to rely on I4.0 technologies.
To ensure that the selected companies met the criteria, we consulted an online database, classifying firms based on their primary ATECO code and revenue. The ATECO code is a designation used by the Italian government to identify the main activity of a firm. Specifically, we chose only companies falling under the ATECO code 01, which includes businesses engaged in the "Cultivation of crops, animal production, hunting, and related services," excluding sub-codes related to livestock and hunting activities. Table 2.1 shows the ATECO codes considered.

Table 2.1 ATECO codes of the companies.

ATECO code	Description
01.10	Cultivation of non-permanent crops, namely plants that do not last more than two seasons. This includes rice and pulses.
01.13	Cultivation of vegetables (including melons) with leaf, stem, fruit, root, bulbs, and tubers (excluding sugar beets and potatoes).
01.20	Cultivation of permanent crops, namely plants that persist in the soil for more than two years, which, despite wilting, regenerate consistently. This includes citrus and oil-bearing fruits.
1.21	Grape farming. Wine production activities from grapes primarily not of own production are excluded.

Following weekly reminders, we gathered responses from 118 companies. Next, we discarded two answers due to incoherent responses and collected the final sample comprising 116 observations.

2.4.2 Questionnaire structure

We divided the questionnaire into 3 main sections. The first focuses on technological capability and aims to assess the technological skills, technological strategy and technological maturity of the company. To measure technological skills we used three items, adapted from Dubey et al. (2019) and Wang et al. (2006). These measure the technology skills of the company's employees, investments in training, and the company's ability to attract staff with advanced technology skills. We used three items to evaluate the company's technological strategy. Items are adapted from Ghobakhloo et al. (2023), Taghizadeh et al. (2020) and Wang et al. (2006) and measure the company's ability to set new technological standards, use technologies to solve problems, and drive innovation in the industry. Finally, we used two items to measure the technological maturity of the company. These measure the firm's ability to integrate and rely on multiple I4.0 technologies. Items were adapted from Ghobakhloo et al. (2023) and Wang et al. (2006).

The second part of the questionnaire investigates how I4.0 technologies affect the social sustainability of agrifood companies. We distinguish three aspects of social sustainability, relating to the management of the supply chain, relations with external stakeholders, and human resources. Specifically, we used three items to assess how technologies influence sustainable supply chain management. Items are adapted from Lu et al. (2012) and Mani et al. (2018) and evaluate if I4.0 technologies help companies establish trust relationships with partners, promote and assess partners' CSR performance. Sustainable stakeholder management was measured with three items, adapted from Mani et al. (2016) and Marshall et al. (2015). These investigate whether I4.0 technologies help the company to consider stakeholders' needs, address consumers' demands, and foster the development of the communities in which the company operates. Finally, we used three items to assess the impact of I4.0 technologies on the sustainable management of human resources. Items are adapted from Gorgenyi-Hegyes et al. (2021) and Mani et al. (2020) and relate to the ability to enhance the healthiness of the workplace, ensure employees' work-life balance, and address workers' needs.

Each variable was measured using a 5-point multi-item Likert scale, ranging from "Strongly disagree" to "Strongly agree." Scales and items are available in the Appendix in table A.1. The last section of the questionnaire includes socio-demographic information about the respondents and inquiries regarding the company's business activity.

2.4.3 Data analysis

Following the hypotheses definition, the development of the theoretical model, and the identification of reliable metrics, we use SEM methodology to analyse data and test hypotheses. We made this choice for 3 main reasons. First, SEM is a popular methodology in business management research and is suitable to investigate technological innovation and adoption issues (Henseler et al., 2016). Several recent studies use SEM to analyse the impact of the adoption of innovative technologies on different aspects of business management, including human resources, knowledge management, and sustainability (Amouei et al., 2023; Dubey et al., 2019; Ghobakhloo et al., 2023; Raut et al., 2019; Sony et al., 2023). Second, SEM enables the evaluation of the effects of latent variables, defined by Rigdon (2016) as conceptual variables that affect the behaviour of other variables in a theoretical model. Consistently, we use SEM to investigate how I4.0 technological capability influences different aspects of the social sustainability of agrifood companies. Third, SEM can be used effectively in exploratory empirical research, provided that the latent variables are framed in an appropriate theoretical context (Rigdon, 2016). Given the lack of empirical studies investigating the impact of I4.0 technologies on the social sustainability of agrifood companies, we referred to the RBV and KBV theories to define technological capability, and to the concept of CSR to investigate agrifood companies' social responsibilities.

As for determining the appropriate sample size, this depends on the complexity of the model and the number of factors. In general, SEM can perform well even with small sample sizes in the analysis of relatively simple models, with reliable and distinct variables (Iacobucci, 2010). Furthermore, if the core population is limited and homogeneous, and if the sample adequately represents the target population, SEM can perform well also with relatively small samples (Rigdon, 2016). Under these assumptions, general rules of thumb suggest that even samples between 50 and 100 observations can prove adequate (Molwus et al., 2013). In this study, we focus on specific segments of Italian agrifood companies and select the companies so that they meet rigorous criteria. Considering the low number of factors and the limited target population, the final sample comprising 116 observations proves sufficient. In line with previous studies, we perform the model evaluation in two phases, using the AMOS 29 (Gerbing & Anderson, 1988) software. First, we use a Confirmatory Factor Analysis (CFA) to test the reliability, validity and fit of the measurement model, which focuses on the relationships between factors and latent variables. In the second we assess the goodness of fit of the structural model, which represents the hypothesized relationships between the latent variables. In this, the literature does not provide a single indicator but suggests evaluating and reporting several measures of model fit (Hair et al., 2019; Henseler et al., 2016; Richter et al., 2017).

Consistent with the hypotheses, in this study we test three different models. In the first model, we test the impact of I4.0 technological capability variables on sustainable supply chain management. In the second model, we test the impact of I4.0 technological capability variables on sustainable stakeholder management. Finally, in the last model, we test the impact of I4.0 technological capability variables on sustainable human resource management. Despite its advantages, SEM presents some weaknesses. Specifically, the definition of the model entails the risk of omitting significant variables or including redundant variables. Both circumstances affect parameter estimation and could bias the results (Tomarken & Waller, 2005). To mitigate these risks, it is important to develop SEM models starting from robust theoretical frameworks (Hair et al., 2019). In this study, we address this weakness by referring to well-established theories and measures. Furthermore, because of the previous issue, the validation of the model does not provide information on potential alternatives. In fact, several equally valid or even superior models might be developed considering different variables and relationships (Tarka, 2018; Tomarken & Waller, 2005). From this perspective, an additional limitation of SEM concerns model re-specification. All changes to the model must be justified by theory, to prevent the inclusion of variables and relationships designed to increase the level of fit, sacrificing coherence and common sense (Tarka, 2018). Finally, SEM cannot account for poor study design, which could lead to incorrect or biased measurements (Rigdon, 2016).

2.5 Results

We present the results in three sections, addressing descriptive analysis, measurement model, and structural model evaluation respectively.

2.5.1 Descriptive analysis

The distribution of responses related to socio-demographic variables and companies' characteristics is shown in tables 2.2 and 2.3. Regarding the respondents, 74.1% are male, 23.2% are female, and 2.7% prefer not to disclose.

Furthermore, 52.6% of the interviewees are top managers in their companies, 24.1% work in production, while the remaining 23.8% are distributed among human resources, R&D, marketing, logistics, and information services. Furthermore, approximately 72% of respondents have at least 10 years of experience in the agrifood industry. As for the companies, we note that all sectors considered in the study are adequately represented in the sample. Most of the companies are headquartered in the northern regions of Italy, and while most firms serve the domestic market, the share of companies primarily targeting foreign markets is significant. Furthermore, the majority are small businesses, with fewer than 50 employees and a revenue of less than 10 million euros. These data align with the characteristics of companies within the Italian agrifood industry, suggesting a good representativeness of the sample.

Table 2.2 distribution of socio-demographic variables (individuals).

Variable (individuals)	Distribution
Gender	
Male	74.1%
Female	23.2%
Division	
Top management	52.6%
Production	24.1%
R&D	6.0%
Human resources	4.3%
Marketing	6.9%
Logistics	4.3%
ICTs	0.8%
Years of experience	
1 – 5	14.6%
6 – 10	12.9%
11 – 20	27.5%
More than 20	44.8%

Table 2.3 distribution of variables related to companies' characteristics.

Variable (companies)	Distribution
ATECO code	
1.10	14.6%
1.13	17.2%
1.20	15.5%
1.21	52.5%
Headquarters (Italy)	
North	42.2%
Central Italy	22.3%
South	21.5%
Islands	12.9%
Primary market	
Italy	66.4%
Europe	23.3%
North and South America	10.3%
Total revenue	

Less than 10 million €	64.7%
Between 10 and 50 million €	25.9%
Over 50 million €	9.5%
Number of employees	
Less than 50 employees	62.1%
Between 50 and 250 employees	31.0%
Over 250 employees	6.9%
Years of activity in the agrifood industry	
Less than 10 years	10.3%
Between 10 and 20 years	12.9%
More than 20 years	76.7%

2.5.2 Measurement models

To test the measurement models, we conducted a Confirmatory Factor Analysis (CFA) for each model, following the recommendations of Hair et al. (2019). The fit indices for the first model show a good model fit (Cmin/df = 1.198 [df = 38] (p = 0.000), CFI = 0.988, IFI = 0.988, TLI = 0.982, RMSEA = 0.041, SRMR = 0.05). The fit indices also show good model fit for the second model (Cmin/df = 1.281 [df = 38] (p = 0.000), CFI = 0.979, IFI = 0.980, TLI = 0.970, RMSEA = 0.049, SRMR = 0.05), and for the third model (Cmin/df = 1.609 [df = 38] (p = 0.000), CFI = 0.963, IFI = 0.964, TLI = 0.946, RMSEA = 0.073, SRMR = 0.05) (Byrne, 2001; Hair et al., 2006).

Construct convergent validity and reliability were assessed using Cronbach's α, Spearman-Brown's coefficient, Composite Reliability (CR) and Average Variance Extracted (AVE) (Chang & Fong, 2010; Fornell & Larcker, 1981; Ghobakhloo et al., 2023; Gleim et al., 2013; Hair et al., 2006; Hair et al., 2019; Iacobucci, 2010; Lewandowska et al., 2023). All factor loadings are greater than 0.5, all the constructs have a Cronbach's α and CR value exceeding the suggested threshold of 0.70 as well the AVE is above the cut-off 0.50, thus, all constructs reached the minimum threshold for a good convergent validity and reliability (table 2.4; table 2.5; table 2.6). Then, to assess discriminant validity, we used the Fornell and Larcker criterion, making sure that the square root of the AVE is greater than the correlation between constructs (Fornell & Larcker, 1981) (table 2.7; table 2.8; table 2.9).

Table 2.4 factor loadings and reliability measures for the model testing the impact of technological capability on sustainable supply chain management.

Construct	Factors	Factor loadings	Cronbach's α / Spearman-Brown's coefficient	CR
Technological skills (TSK)	TSK_1	0.729	0.788	0.792
	TSK_2	0.791		
	TSK_3	0.722		
Technological strategy (TST)	TST_1	0.815	0.812	0.822
	TST_2	0.676		
	TST_3	0.838		
Technological maturity (TMT)	TMT_1	0.844	0.766*	0.769
	TMT_2	0.735		
Sustainable supply chain management (SSC)	SSC_1	0.851	0.892	0.894
	SSC_2	0.892		
	SSC_3	0.831		

***Spearman-Brown's coefficient value for the two-item scale**

Note. N = 116; Model fit (Cmin/df = 1.198 [df = 38] (p = 0.000), CFI = 0.988, IFI = 0.988, TLI = 0.982, RMSEA = 0.041, SRMR = 0.05).

Table 2.5 factor loadings and reliability measures for the model testing the impact of technological capability on sustainable stakeholders' management.

Construct	Factors	Factor loadings	Cronbach's α / Spearman-Browns' coefficient	CR
Technological skill (TSK)	TSK_1	0.700	0.788	0.791
	TSK_2	0.807		
	TSK_3	0.730		
Technological strategy (TST)	TST_1	0.815	0.812	0.822
	TST_2	0.671		
	TST_3	0.842		
Technological maturity (TMT)	TMT_1	0.836	0.766*	0.768
	TMT_2	0.742		
Sustainable stakeholders' management (SST)	SST_1	0.805	0.788	0.784
	SST_2	0.693		
	SST_3	0.718		

***Spearman-Brown's coefficient value for the two-item scale.**

Note. N = 116; Model fit (Cmin/df = 1.281 [df = 38] (p = 0.000), CFI = 0.979, IFI = 0.980, TLI = 0.970, RMSEA = 0.049, SRMR = 0.05).

Table 2.6 factor loadings and reliability measures for the model testing the impact of technological capability on sustainable human resources management.

Construct	Factors	Factor loadings	Cronbach's α / Spearman-Brown's coefficient	CR
Technological skills (TSK)	TSK_1	0.715	0.788	0.791
	TSK_2	0.781		
	TSK_3	0.744		
Technological strategy (TST)	TST_1	0.818	0.812	0.822
	TST_2	0.676		
	TST_3	0.835		
Technological maturity (TMT)	TMT_1	0.822	0.766*	0.767
	TMT_2	0.755		
Sustainable human resources management (SHR)	SHR_1	0.820	0.893	0.896
	SHR_2	0.872		
	SHR_3	0.889		

***Spearman-Brown's coefficient value for the two-items scale.**
Note. N = 116; Model fit (Cmin/df = 1.609 [df = 38] (p = 0.000), CFI = 0.963, IFI = 0.964, TLI = 0.946, RMSEA = 0.073, SRMR = 0.05).

Table 2.7 validity measures for the model testing the impact of technological capability on sustainable supply chain management.

AVE is displayed on the main diagonal. Squared correlations between constructs off-diagonal.				
Construct	TSK	TST	TMT	SSC
TSK	**0.608**			
TST	0.295	**0.559**		
TMT	0.581	0.117	**0.626**	
SSC	0.108	0.510	0.062	**0.737**

Abbreviations: SSC: sustainable supply chain management, TSK: technological skills, TST: technological strategy, TMT: technological maturity.

Table 2.8 validity measures for the model testing the impact of technological capability on sustainable stakeholders' management.

AVE is displayed on the main diagonal. Squared correlations between constructs off-diagonal.				
Construct	TSK	TST	TMT	SST
TSK	**0.608**			
TST	0.291	**0.558**		
TMT	0.582	0.111	**0.625**	
SST	0.028	0.549	0.028	**0.548**

Abbreviations: SST: sustainable stakeholders' management, TSK: technological skills, TST: technological strategy, TMT: technological maturity.

Table 2.9 validity measures for the model testing the impact of technological capability on sustainable human resources management.

AVE is displayed on the main diagonal. Squared correlations between constructs off-diagonal.				
Construct	TSK	TST	TMT	SHR
TSK	**0.608**			
TST	0.296	**0.558**		
TMT	0.588	0.117	**0.623**	
SHR	0.097	0.370	0.127	**0.741**

Abbreviations: SHR: sustainable human resources management, TSK: technological skills, TST: technological strategy, TMT: technological maturity.

2.5.3 Structural models

The structural model tests the hypothesized relationships between latent variables. To test the structural models, we drew the paths representing the hypothesized relationships between the variables. The fit indices confirm good model fit for the first model (Cmin/df = 1.198 [df = 38] (p = 0.000), CFI = 0.988, IFI = 0.988, TLI = 0.982, RMSEA = 0.041, SRMR = 0.05), as well as for the second model (Cmin/df = 1.281 [df = 38] (p = 0.000), CFI = 0.979, IFI = 0.980, TLI = 0.970, RMSEA = 0.049, SRMR = 0.05), and the third model (Cmin/df = 1.609 [df = 38] (p = 0.000), CFI = 0.963, IFI = 0.964, TLI = 0.946, RMSEA = 0.073, SRMR = 0.05) (Byrne, 2001;

Hair et al., 2006). Tables 2.10, 2.11 and 2.12 show the results of the assessment of the structural models, and table 2.13 provides an overview of the hypotheses. The results allow us to support hypotheses H1.a, H2.a and H3.a, confirming the positive effect of I4.0 technological skills on all three dimensions of social sustainability. Results also don't support hypotheses H1.b, and H3.b while at the same time rejecting hypothesis H2.b, which suggests a significant negative relationship between I4.0 technological strategy and sustainable stakeholder management. Finally, hypotheses H1.c and H2.c, are not supported, while hypothesis H3.c is supported, suggesting a positive relationship between I4.0 technological maturity and sustainable human resources management.

Table 2.10 structural equation model coefficients for the first model (sustainable supply chain management).

Paths	Standardized coefficients
TSK → SSC	0.773**
TST → SSC	-0.191
TMT → SSC	0.131

Note. N = 116; Model fit (Cmin/df = 1.198 [df = 38] (p = 0.000), CFI = 0.988, IFI = 0.988, TLI = 0.982, RMSEA = 0.41, SRMR = 0.05). **** p < .01.** Abbreviations: SSC: sustainable supply chain management, TSK: technological skills, TST: technological strategy, TMT: technological maturity.

Table 2.11 structural equation model coefficients for the second model (sustainable stakeholders' management).

Paths	Standardized coefficients
TSK → SST	0.946**
TST → SST	-0.551*
TMT → SST	0.273

Note. N = 116; Model fit (Cmin/df = 1.281 [df = 38] (p = 0.000), CFI = 0.979, IFI = 0.980, TLI = 0.970, RMSEA = 0.049, SRMR = 0.05). **** p < .01; *p < .05**. Abbreviations: SST: sustainable stakeholders' management, TSK: technological skills, TST: technological strategy, TMT: technological maturity.

Table 2.12 structural equation model for the third model (sustainable human resources management).

Paths	Standardized coefficients
TSK → SHR	0.667**
TST → SHR	-0.365
TMT → SHR	0.409*

Note. N = 116; Model fit (Cmin/df = 1.609 [df = 38] (p = 0.000), CFI = 0.963, IFI = 0.964, TLI = 0.946, RMSEA = 0.073, SRMR = 0.05). **** p < .01; *p < .05**. Abbreviations: SHR: sustainable human resources management, TSK: technological skills, TST: technological strategy, TMT: technological maturity.

Table 2.13 summary of hypotheses and results.

Hypothesis	Results
H1.a: technological skills positively influence sustainable supply chain management	Supported
H1.b: technological strategy positively influences sustainable supply chain management	Not supported
H1.c: technological maturity positively influences sustainable supply chain management	Not supported
H2.a: technological skills positively influence sustainable stakeholders' management	Supported
H2.b: technological strategy positively influences sustainable stakeholders' management	Not supported
H2.c: technological maturity positively influences sustainable stakeholders' management	Not supported
H3.a: technological skills positively influence sustainable human resources management	Supported
H3.b: technological strategy positively influences sustainable human resources management	Not supported
H3.c: technological maturity positively influences sustainable human resources management	Supported

2.6 Discussion

The results provide mixed evidence and prompt reflection on the complex relationship between the adoption of I4.0 technologies and social sustainability in agrifood companies.

First, we observe how results support hypotheses H1.a, H2.a, and H3.a, emphasizing the positive impact of I4.0 technological skills on all three dimensions of sustainability. In line with previous contributions, training is key not only to ensuring the effective integration of new solutions into business but also to creating healthier work environments (Caputo et al., 2019; Neumann et al., 2021; Sony & Mekoth, 2022). As shown by Cannas (2023) and Rijswijk et al. (2021), this could be particularly important for companies performing cultivation activities, where traditional business practices often prevail. Several studies suggest that one of the main obstacles to the adoption of I4.0 technologies in the agrifood industry is the lack of familiarity of agrifood workers with innovative solutions. This generates scepticism and resistance, stressing the importance of investing in the development of technological skills. Furthermore, investing in employee training may promote an innovation-oriented culture, eliciting the adoption of I4.0 technologies (Mahdad et al., 2022). Finally, the development of technological skills can contribute to the creation of healthier work environments, empowering employees to manage and supervise processes, and shifting from executors to decision-makers (Martin et al., 2022; Neumann et al., 2021). Again, this may be especially relevant for companies performing cultivation activities, that may leverage I4.0 technologies to reduce manual labour and revolutionize the execution of field activities (Arvanitis & Symeonaki, 2020).

Interestingly, the results also suggest that the development of I4.0 technological skills enhances the social sustainability of agrifood companies in terms of supply chain management and relationships with stakeholders. However, this issue is currently under-investigated. Our results highlight that I4.0 technologies might raise awareness among workers in the agrifood industry regarding supply chain issues and external stakeholders' demands by favouring the development of transversal skills and reducing the time dedicated to cultivation activities. Also, several studies explain how the adoption of blockchain and IoT systems requires agrifood companies to develop not only technological expertise but also managerial skills, enabling them to significantly affect supply chain dynamics, potentially helping companies build trust relationships with partners and increase security and accountability (Blanka et al., 2022; David et al., 2022). This can help companies upstream of the agrifood supply chain develop a better understanding of the dynamics of the industry, increasing coordination between partners and tightening links between supply chain actors and external stakeholders (Clapp & Ruder, 2020; Glavee-Geo et al., 2022).

The findings also shed light on the complexity of the relationship between technological strategy and social sustainability. Surprisingly, the results confute hypothesis H2.b, highlighting a significant, yet negative relationship between I4.0 technological strategy and sustainable stakeholders' management. One possible explanation is that, by favouring automation, the adoption of I4.0 technologies could reduce human involvement in business operations. This could lead to a reduction in interactions with stakeholders and consequently reduce the firm's ability to address stakeholders' demands. Furthermore, the process of integrating advanced technologies could require considerable economic and organizational resources, which could otherwise be used by management to improve relations with stakeholders and implement activities aimed at satisfying their needs.

However, it is important to stress how this explanation might contradict some findings in the literature, which suggest that the adoption of I4.0 technologies is an important step for agrifood companies to address some long-standing social sustainability issues. For example, according to Rijswijk et al. (2021), technological innovation may provide significant opportunities for the development of rural communities, whereas several studies argue that the use of advanced tracking systems could help agrifood companies regain consumers' trust and effectively enhance the transparency and accountability of the supply chain (Dal Mas et al., 2023; Majdalawieh et al., 2021; Motta et al., 2020).

Regarding I4.0 technological maturity, the results provide mixed evidence, and support only hypothesis H3.c, suggesting a significant positive relationship between I4.0 technological maturity and sustainable human resources management. This finding proves that the seamless integration of different I4.0 technologies has a positive effect on the quality of the working environment. This aligns with recent studies suggesting that the greatest benefits of adopting I4.0 technologies emerge when companies leverage the synergies of different technological solutions (Annosi et al., 2020). Mazzetto et al. (2019) and Mahdad et al. (2022) demonstrate how the combination of IoT and farm management systems allows agrifood companies to access real-time data on weather conditions and crop health, enabling the development of predictive models to support activity planning. This reduces the dependence of activities on uncontrollable natural factors, improving labour management and reducing operator workloads. Similarly, Sam et al. (2022) show how the combination of smart information systems and Big Data analytics enables the automation of traditionally manual tasks, significantly improving the working conditions of horticultural workers. Furthermore, the results suggest that the integration of I4.0 technologies into business processes represents an opportunity for human resources empowerment in an industry characterized by traditional working practices. This also contrasts previous findings suggesting that technological innovation in the agrifood industry could have negative social implications in terms of labour management, leading to job losses and the exclusion of workers with low technological skills (Prause, 2021).

Finally, the results do not support hypotheses H1.c and H2.c, suggesting that the relationship between I4.0 technological maturity and the improvement of social performance in agrifood companies in terms of supply chain and stakeholders' management is not significant. This conflicts with previous studies suggesting that the adoption of I4.0 technologies is one of the main drivers through which agrifood companies can address stakeholders' demands and build more transparent and accountable supply chains (Majdalawieh et al., 2021; Sander et al., 2018). Analysing this result, we posit that the characteristics of the sampled companies, primarily involved in cultivation activities, may have influenced the results. In contrast, much of the literature on I4.0's impact on agrifood supply chains tends to focus on challenges related to processing and transportation (Corallo et al., 2020; Kamble et al., 2019). Moreover, several studies examining the role of product tracking systems in supply chain sustainability focus on specific product categories, indicating that outcomes may vary depending on the unique characteristics of the product or market (Antonucci et al., 2019; Salah et al., 2019). Therefore, we emphasize the need for studies that focus on investigating how different I4.0 technologies and applications can promote social sustainability in the agrifood industry at multiple supply chain levels beyond the cultivation stage and taking into account the specificities of different product categories.

2.7 Conclusions

The adoption of I4.0 technologies is one of the main drivers of the sustainable development of the agrifood industry (Lezoche et al., 2020; B. S. Miranda et al., 2019). However, the effects of technological innovation on the social sustainability of agrifood companies remain unclear. Indeed, recent studies suggest that the adoption of I.40 technologies may have significant social implications for agrifood companies, affecting labour management, supply chain accountability, and relationships with key stakeholders, including governments and consumers (Chandan et al., 2023; Prause, 2021; Rijswijk et al., 2021). Despite this, available literature focuses on the relationship between environmental and economic benefits, while social sustainability implications are currently under-investigated, especially from an empirical perspective.

This chapter aimed to help bridge this gap by providing evidence of the impact of I4.0 technologies on the social sustainability of companies in the agrifood industry. To this end, we use data from 116 Italian agrifood companies to validate a theoretical model explaining how the adoption of I4.0 technologies influences the social sustainability of agrifood companies. Specifically, this study focuses on agrifood companies performing cultivation activities, which face unique and relevant social sustainability challenges related to labour, supply chain, and stakeholders' management.

From a theoretical perspective, this chapter offers two main contributions. First, it validates a conceptual model assessing the impact of I4.0 technologies on the social sustainability of agrifood companies. This advances the literature by providing a framework that can guide future studies on the social implications of technological innovation in the agrifood industry. Second, this study is one of the few to provide empirical evidence of the impact of I4.0 technologies on different aspects of the social sustainability of agrifood companies. This helps explain how technological innovation may influence social sustainability in the agrifood industry and identify further research opportunities. Results show that the development of I4.0

technological skills has a positive impact on all three dimensions of social sustainability. This is consistent with recent literature suggesting that the adoption of I4.0 technologies promotes the development of managerial skills, shifting the role of agricultural workers from executors to decision-makers. Furthermore, the development of I4.0 technological skills enables the use of advanced solutions, which can support operators in the execution of physically demanding tasks (Alves et al., 2023; Lioutas et al., 2021). I4.0 technological skills also positively affect the sustainable management of the supply chain and stakeholder relations, although the reasons are currently under-investigated.

Finally, the results highlight the complexity of the relationship between I4.0 technological strategy and social sustainability. The results reveal a negative relationship between I4.0 technological strategy and sustainable stakeholders' management, somewhat contradicting recent studies suggesting that an adequate technological innovation strategy is a crucial stepping stone in assisting agrifood companies regain the trust of consumers and society. Advancing an explanation, we hypothesize that the adoption of I4.0 absorbs resources and attention that could have been otherwise directed to address stakeholders' demands. Finally, a positive relationship was found between I4.0 technological maturity and human resources management, confirming that I4.0 technologies may help companies create healthier work environments, in combination with the development of I4.0 technological skills.

As for practical implications, this study can help managers analyse and reap the social benefits of adopting I4.0 technologies. Findings show that the introduction of innovative technologies represents a significant opportunity to develop employees' skills and improve the quality of working conditions, balancing the workloads of field operators.

Automation could effectively support cultivation activities, while the use of predictive models could reduce the impact of unpredictable natural factors. Moreover, acquiring advanced and transversal technological skills could provide benefits that go beyond the management of cultivation activities. The use of data provided by modern information systems could simplify communication and coordination with partners and enhance supply chain security, with positive effects on the relationships with stakeholders, including governments and consumers. Finally, the results invite managers to carefully assess how the company's I4.0 technological strategy and maturity affect the various dimensions of social sustainability. The findings warn about the risk of focusing exclusively on the company's needs and losing sight of the interests of supply chain partners and external stakeholders.

Despite its contributions, this work is not exempt from limitations. Concerning the sample, this study is based on data obtained from companies operating in specific stages of the Italian agrifood industry. In particular, the study focuses on companies performing cultivation activities in a highly industrialized context. Thus, while adequate to the scope of the chapter, the sample has limitations. First, it does not include companies that perform product processing and distribution activities. Companies in the meat industry are also excluded. This affects the generalizability of the results, as the study does not provide information on the advantages that I4.0 technologies can offer to such companies. Furthermore, by focusing on a single country, the study does not account for socioeconomic factors that might affect the results. Future studies can extend the analysis by carrying out cross-country investigations or by focusing on different geographic areas. Another limitation of the study concerns the use of sociodemographic variables. While providing useful information to outline the profile of the respondents and validate the information sources, the available observations prevented us from capturing any differences in the perceptions of respondents based on variables such as gender or age. Future contributions could focus on assessing how sociodemographic variables mediate individuals' perception of the impact of I4.0 technologies on the social sustainability of agrifood companies. Finally, we reflect on possible limitations in the theoretical model. Specifically, the absence of previous studies investigating the impact of I4.0 technologies on the social sustainability of agrifood leads to a lack of established metrics and indicators. In this study, we address this shortcoming by referencing established theories such as the RBV to model the technological capability of the company, and the literature on CSR to investigate the multiple facets of social sustainability in the agrifood industry. Despite our efforts to identify all relevant variables, this may have caused us to overlook some important factors. Thus, we elicit future research to extend the analysis and provide additional elements to our framework. Lastly, we point out that this study investigates the impact of I4.0 technologies on the social sustainability of agrifood companies holistically. Therefore, future contributions could obtain different results by focusing on individual technologies or specific applications.

CHAPTER III – Exploring Blockchain Adoption in the Italian Wine Industry: Insights from a Multiple Case Study.

Summary

This chapter aims to contribute to bridging a gap in the literature identified in the first chapter. Specifically, the literature review revealed a lack of empirical studies examining the adoption of innovative technologies in the agrifood sector from a managerial and organizational perspective. This chapter helps address this gap by focusing on one of the most relevant Industry 4.0 technology applications, investigating the challenges, drivers, and requirements for blockchain adoption in the Italian wine industry. This is a relevant issue for two main reasons. First, due to the potential of blockchain-based product tracking systems to help companies in the wine industry address long-standing issues related to counterfeiting and the marketing of high-end wines. Second, due to the limited diffusion of the technology within the industry, which contrasts with the disruptive role attributed to blockchain by the scientific literature. Consistently, this chapter leverages a multiple case study approach to gather the perceptions of managers in Italian wine companies, analyse challenges and opportunities, and identify the key requirements of a blockchain-based product tracking system. In doing so, the chapter contributes to the literature by introducing new elements in the literature on blockchain adoption. As for practical implications, this study provides much-needed empirical evidence on the implications of blockchain technology adoption in the wine industry, offering valuable recommendations to policymakers and practitioners to promote the adoption of blockchain. Finally, this study aligns with the results of the collaboration with Euro.Soft s.r.l., which will be presented in the following chapter, providing a holistic perspective on the issue of blockchain adoption in the Italian wine industry. This chapter is adapted from an article accepted for publication in the Wine Economics and Policy journal (Cricelli et al., 2024).

3.1 Introduction

The modern agrifood industry faces key challenges due to its pivotal role in sustaining the growth and development of society. This is exacerbated by globalization, which increases the complexity and risks of managing supply chains, leading to food safety issues and demands for higher quality and accountability from consumers and governments (Chandan et al., 2023;

Smith & McElwee, 2020). Agrifood companies are also pressured to build more transparent and equitable supply chains (Glavee-Geo et al., 2022; Krzyzanowski Guerra & Boys, 2022). The adoption of advanced tracking systems may provide a solution by helping streamline information and product flows, improve coordination, and enhance transparency throughout agrifood supply chains (Dal Mas et al., 2023; Kamilaris et al., 2019). Blockchain-based systems, in particular, may offer greater security, integrity, and accountability compared to traditional ICTs (Chittipaka et al., 2023; Tandon et al., 2021). This is crucial in tracking agrifood products, which are especially sensitive to environmental factors, including temperature or humidity, and must meet high safety standards (Singh et al., 2022; Vilas-Boas et al., 2023).

From this perspective, a particularly compelling scenario concerns the adoption of tracking systems in the wine industry, which must also contend with serious counterfeiting, imitation, and label adulteration issues (Malisic et al., 2023; Tandon et al., 2021). Indeed, while many agrifood products are treated as commodities, high-end wines can be considered premium products, enabling companies to focus on differentiation strategies (Bandieri & Castellini, 2023; Carbone et al., 2023; Le et al., 2023).

Since the origin and variety of grapes play a crucial role in determining wine quality and influencing consumers' choices, producers and consumers require reliable systems to guarantee product authenticity (Carbone et al., 2023; Saurabh & Dey, 2021). This is especially true also due to the proliferation of unreliable food certification schemes, which fuel trust and communication issues between companies and consumers (Hamilton & Raison, 2019; Rejman et al., 2023). Despite this, the diffusion of advanced product tracking systems in the wine industry remains limited and it is essential to investigate the reasons explaining the low adoption rates.

However, this topic currently remains under-investigated, as most studies adopt one of two approaches. On the one hand, several articles focus on describing the impact and main advantages of blockchain-based solutions for supply chain management compared to traditional tracking systems (Agi & Jha, 2022; Ahmed et al., 2022; Kumar et al., 2020; Li et al., 2022; Markus & Buijs, 2022). These inquiries adopt a technology-centric perspective and do not consider specific applications in the agrifood industry. On the other, some chapters focus on investigating the potential of advanced tracking systems for a variety of applications in the agrifood industry (Dal Mas et al., 2023; Hasan et al., 2024; Kamilaris et al., 2019; Kumar et al., 2022; Zhao et al., 2019). However, most studies provide purely theoretical contributions. While offering valuable insights, these articles typically stress the novelty and benefits of blockchain solutions over implementation challenges and business implications.

Indeed, it is only recently that the first studies focusing on the adoption of blockchain-based systems in the wine industry started to emerge (Brookbanks & Parry, 2022; Danese et al., 2021; Silvestri et al., 2023; Tiscini et al., 2020). These investigations suggest that the adoption of blockchain in the wine industry entails significant managerial and organizational complexities which require careful analysis. For example, Brookbanks and Parry (Brookbanks & Parry, 2022) show how the use of blockchain systems does not remove the need to implement trust-building processes between wineries, partners, and consumers. Galati et al. (2021) suggest that effective blockchain adoption depends on wineries' ability to invest and redefine knowledge management processes within the organization. Cordeiro and Olsen (2021) investigate the differences in the diffusion of blockchain in European and Chinese wine value chains, emphasizing the influence of the environment and the international context.

Despite the contributions, most of the articles focus on isolated success stories. Due to the limited diffusion of blockchain in the wine industry, this helped provide much-needed evidence of how the adoption of advanced tracking systems may affect wineries' business models and performances. At the same time, this led to a somewhat biased perspective, emphasizing the benefits and positive outcomes over complexities. This limitation is exacerbated by the lack of studies analysing failures in the adoption of blockchain systems within the agrifood industry. This is likely due to the reluctance of companies to openly discuss unsuccessful experiences, as businesses may fear reputational damage or competitive disadvantages. Moreover, another factor that may have contributed to shaping this unbalanced perspective on blockchain's potential is the absence of analyses focusing on pilot cases. Such studies could provide valuable insights into implementation challenges, helping to paint a more comprehensive picture of both the opportunities and obstacles associated with the integration of advanced tracking technologies in the sector.

This highlights a gap in the literature related to the lack of studies investigating the challenges of blockchain adoption in the wine industry, and the in-depth analysis of the requirements that tracking systems must possess to meet the needs of actors in wine supply chains. This study aims to help bridge this gap and offer a new perspective by analysing the challenges, drivers and requirements of blockchain-based solutions in the wine industry.

Additionally, we note how most studies investigating specific applications of tracking systems in supply chains focus on large-scale projects, involving multinationals, tech companies and several partners around the world (Bumblauskas et al., 2020; Kshetri, 2018; Sarker et al., 2021). This approach is not suitable for the wine industry, due to the prevalence of SMEs and local productions in the sector. Thus, we try to help bridge this gap by providing an empirical investigation of the drivers and challenges of blockchain adoption for SMEs in the wine industry. Ultimately, in this chapter we aim to answer the following research question:

RQ4) What are the drivers and challenges of adopting blockchain-based systems for SMEs in the wine industry?

To answer this question, we adopt a multiple case study approach, focusing on the case of the Italian wine industry. Specifically, we investigated companies' perception of blockchain solutions by performing semi-structured interviews with the managers of 16 Italian wineries. Then, we use thematic analysis, supported by a three-step coding process, to identify overarching themes and develop the results. In selecting the cases, our primary goal was to obtain a detailed picture of the current situation of traceability and blockchain adoption in the Italian wine industry. The originality of the study lies mainly in two aspects. It is one of the first studies to investigate the problem of blockchain adoption in the agrifood industry concerning a specific application, namely product tracking in the wine industry. Second, this study does not analyse single cases, but adopts a multiple-case study approach, leading to a nuanced perspective introducing new relevant elements into the debate.

Finally, this study has important theoretical and practical implications. From a theoretical perspective, it effectively complements the results of previous literature, by providing an in-depth analysis of key managerial and organizational factors influencing wineries' decision to adopt blockchain technology. It also advances the theory by analysing the requirements that a blockchain system must possess to meet the needs of SMEs in the wine industry. In terms of practical implications, this study helps wine companies assess the opportunities and implications of adopting blockchain. Furthermore, it provides policymakers and governments with suggestions on how to support the diffusion of advanced tracking systems in the wine industry.

The rest of the chapter is organized as follows: paragraph 3.2 provides an overview of the main features of blockchain technology. The following section provides a brief yet rigorous review of the available literature. Then, the case study and thematic analysis methodology are described in detail. Next, the results are presented and discussed. Finally, the chapter concludes by providing some useful theoretical and practical implications.

3.2 Blockchain technology

Blockchain technology began to gain popularity in 2008 when a group of anonymous authors under the pseudonym Satoshi Nakamoto proposed a blockchain-based solution for exchanging digital assets using the newly created cryptocurrency Bitcoin (Nakamoto, 2008). This was designed to solve the issue of double spending in financial transactions, whereby in the absence of a central authority malicious actors could reuse the same asset multiple times and gain undue profits. Crucially, Nakamoto's solution advanced the idea of ensuring the security and transparency of financial transactions in public networks without the need for a central authority.

From there, scholars and practitioners quickly explored the implications of adopting blockchain technology, even beyond financial applications. Conceptually, blockchain-based systems allow for seamless tracking of digital assets, enabling secure transactions even in low-trust environments. This could be applied to any type of supply chain or network requiring a reliable way to track assets and verify transactions (Wang et al., 2019; Zheng et al., 2017). Furthermore, by eliminating the need for a central authority, blockchain-based systems would reduce transaction costs and times and could lead to the creation of decentralized environments, favouring the sharing of information and power (Agi & Jha, 2022; Antonucci et al., 2019). This could be key in many supply chain applications, where power asymmetries and information control hinder an equitable distribution of value (Kamilaris et al., 2019; Leduc et al., 2021). Finally, in combination with effective methods to connect digital and real-world environments, the use of blockchain-based systems would enhance product tracking throughout the supply chains, increasing the security and accountability of sensitive industries, including healthcare and agrifood (Esfahbodi et al., 2022; Griggs et al., 2018; Queiroz et al., 2021; A. Sharma et al., 2023).

To understand how the adoption of blockchain could help companies achieve such advantages, it is necessary to analyse the architecture, the features and the most significant technological developments. In essence, blockchain can be thought of as a distributed electronic ledger, shared among participants in a network (Kumar et al., 2020; Saberi et al., 2019). In a public blockchain, each participant can be assigned a node, which serves as an access point to the blockchain system. Participants can read the ledger or issue transactions to exchange assets (Saberi et al., 2019; Wang et al., 2019). For efficiency reasons, transactions are not handled individually but are bundled together in blocks. Blocks gather transactions that occur in the same timeframe and are referenced through unique identifiers called hashes. Aside from the first block, called the genesis, hashes are also used as pointers, linking each block to those that preceded it (Novo, 2018; Vilas-Boas et al., 2023). Thus, it is possible to trace every transaction involving an asset to determine its state and ownership.

When a certain number of transactions are executed and a new block is created, it must be verified according to pre-established criteria. Depending on the way transactions are verified, different types of consensus mechanisms are defined (Bamakan et al., 2020; Zheng et al., 2017). As for the original solution proposed by Nakamoto, blocks are verified by nodes called miners, who compete with each other and use significant computational power to verify transactions and earn rewards (Nakamoto, 2008). Once the transactions in a block are verified, it is timestamped, appended to the blockchain, and broadcast to all other nodes in the system (Singh et al., 2022; Treiblmaier, 2018). Thus, a unique chain of verified transactions is created and recorded on a shared electronic ledger, which is replicated and accessible by each node. Thus, each actor in the network gains a real-time view of the transactions that have occurred, ensuring transparency and accountability.

Security is also ensured, as any changes made to already verified blocks cause a discrepancy between the hashes of the altered blocks and the adjacent ones, making tampering evident and deterring attacks by malicious entities (Kumar et al., 2020; Reyna et al., 2018). Finally, the privacy of the actors is guaranteed through the use of coded IDs and asymmetric cryptography to protect the identities of the parties involved in a transaction (Christidis & Devetsikiotis, 2016; Singh et al., 2020).

To conclude this section, we stress that blockchain-based solutions can vary in terms of their architecture, mechanisms, and inherent properties, depending on the type of system considered. In general, the literature distinguishes three fundamental types of blockchain systems: public, consortium, and private blockchains (Bamakan et al., 2020; Nguyen & Kim, 2018). Public blockchains are open, decentralized networks that allow anyone to join, participate, and validate transactions without needing any prior approval. As such, these systems are permissionless, inviting anyone willing to contribute computational power and follow network protocols. Public blockchains emphasize transparency and security, but they can also face scalability and speed challenges due to the high level of public participation (Leduc et al., 2021; Zheng et al., 2017).

In contrast, consortium blockchains operate as semi-decentralized networks, where access and participation are limited to a specific group of entities, often within a particular industry or partnership. In other instances, information is available for anyone to read but writing and validation permission is restricted to specific entities. These blockchains are widely used in enterprise environments, to enhance transparency and distribute power between multiple actors instead of a single central authority (Bamakan et al., 2020).

Finally, private blockchains are entirely permissioned systems. In these networks, access is strictly controlled, and only trusted participants within an organization or network can validate and participate in transactions. Private blockchains are ideal for companies that require high levels of data privacy and control, such as for internal record-keeping or secure document management. At the same time, the centralized nature of private blockchains undermines one of the key features of blockchain systems and proves suitable for contexts where regulation and control are particularly felt (Helliar et al., 2020; Lu et al., 2020). Overall, each of these blockchain types addresses specific needs and priorities, illustrating the flexibility of blockchain technology and its potential applications across diverse contexts.

3.2.1. Consensus in blockchain

Supporting asset exchange in low-trust environments, consensus is a core dynamic of all blockchain-based systems (Yang et al., 2019; Zheng et al., 2017). At the same time, the typology and architecture of the systems significantly influence the mechanisms used to reach consensus. From this perspective, a key parameter is the degree of centralization of the system. In general, public blockchains, which are completely decentralized, implement consensus algorithms that are different from those in consortium or private blockchain networks, which feature increasing degrees of centralization and assign one or more actors the task of controlling and verifying transactions.

Consistently, two main categories of consensus algorithms can be distinguished. Proof-based algorithms require participants to provide ownership of a specific resource, such as computational power, coins, or storage space to gain the right to validate transactions. These are common in public blockchains, as the required resource serves as proof of investment in the network, discouraging attacks by malicious entities (Bamakan et al., 2020). In voting-based algorithms, actors actively communicate and vote on the validity of transactions. These are popular in consortium or private blockchains where the actors are known and finite in number. The need to reach a shared consensus through voting protects against interference from potentially malicious actors (Lashkari & Musilek, 2021). Regardless, since verifying transactions is costly, actors willing to perform such activities are often rewarded for their efforts. This dynamic is particularly relevant in public blockchains where potential validators, called miners, compete to verify transactions and earn rewards, typically in the form of cryptocurrencies (Hughes et al., 2019; Vilas-Boas et al., 2023).

Among the most well-known proof-based algorithms are the Proof-of-Work (PoW) and Proof-of-Stake (PoS) algorithms. In PoW algorithms, miners compete to find a nonce (number used once) that, when used in a special hash function, generates a hash value that meets specific conditions. It's worth noting that generating such a nonce requires time, energy and high computational capabilities. Thus, miners are incentivized to participate by rewarding them with currency (Xie et al., 2023). In PoS algorithms, validators are chosen semi-randomly based on their ownership of a specific resource used in the network, such as a currency. The more resources a node owns, the more likely it is to be designated as a validator. This not only reduces the energy consumption of the system but also reduces the risk of validators acting against the network. This is the type of consensus algorithm used in Ethereum blockchains (Bamakan et al., 2020).

Bamakan et al. (2020) propose a coherent framework for evaluating consensus algorithms in blockchain systems. The authors consider four fundamental dimensions: algorithm throughput, profitability of mining, degree of centralization, and vulnerability. Throughput refers to the number of transactions that the network can validate within a given timeframe. It depends on several factors, including the number of transactions processed per second, block creation latency, validation times, and block size. Profitability, on the other hand, is influenced by rewards, transaction fees, the computational power required for validation, and hardware dependencies. The degree of centralization relates to the distinction between public, consortium, and private blockchains. This dimension explains the overall governance of the blockchain. Finally, vulnerability assesses the resilience of the consensus algorithm against various types of attacks.

3.2.2 Smart contracts

The concept of smart contracts was first described by Nick Szabo in the mid-1990s (Szabo, 1997). However, it was only the development of blockchain technology that enabled the creation of smart contracts respecting Szabo's original vision. In general, these can be thought of as computer programs that enable the verification and enforcement of contractual agreements in a digital environment (Hewa et al., 2021; Rouhani & Deters, 2019).

In blockchain systems, smart contracts can be used to ensure that transactions meet specific criteria or to perform particular operations on a transaction. Blockchain systems are optimal environments for storing and executing smart contracts for two key reasons. First, their code can be stored directly on the blockchain. This makes smart contracts transparent and enables validation of transactions that use the program (Ante, 2021). Second, in blockchain systems, smart contracts can be associated with unique addresses. The address provides an easy way to invoke a contract to operate on a transaction (Christidis & Devetsikiotis, 2016).

Although simple smart contracts were initially implemented on the Bitcoin blockchain, one of the most popular platforms for running smart contracts today is Ethereum (Kushwaha et al., 2022), for two reasons. First, Bitcoin was built primarily for financial applications based on the exchange of digital assets. In contrast, Ethereum was designed with high-level programming languages that allow for greater flexibility (Rouhani & Deters, 2019). Thus, it is easier for smart contracts in Ethereum to perform a variety of operations and controls. Secondly, Ethereum uses an account-based system that distinguishes between externally owned and contract accounts. Contract accounts contain the code and an identifying address of the smart contracts, which users can use to invoke the program so it can execute operations on a transaction (Zhang et al., 2019). Ideally, smart contracts may reflect and enforce agreements between parties, subjecting the exchange of digital assets to the same conditions of the real world (Ante, 2021; Khan et al., 2021). Consistently, most of the recent proposals for supply chain management applications of blockchain technology envision the use of smart contracts both to support product tracking and to provide evidence that specific contractual conditions are being met throughout the supply chain (Dos Santos et al., 2021; Griggs et al., 2018).

At this point, it's worth noting that, due to the additional power consumption and the extra activities performed, the execution of smart contracts is often subject to the payment of fees, which in the case of Ethereum are paid in Gas, a fraction of Ether (Hewa et al., 2021).

Wang et al., (2019) propose a framework for analysing the architecture and main elements of smart contracts using a six-layer conceptual model. The infrastructure layer provides a trusted development and execution environment along with reliable data sources, known as oracles. These are reliable sources of external data, which may be critical to contract functionality.

The contracts layer stores contractual terms, response rules, and interaction protocols. Interaction protocols defined in this layer regulate user access and inter-contract communication, crucial for maintaining consistency with the development platform’s requirements and stakeholder intentions.

The operations layer ensures the integrity and reliability of the smart contracts through the implementation of formal verification and security mechanisms.

Next, the intelligence layer could be used to introduce adaptation and learning patterns into smart contracts. While current implementations often lack sophisticated intelligence, this suggests the potential for contracts to handle complex scenarios autonomously.

The manifestations layer translates the core functionalities into actionable computer programs, including applications, interfaces and front-end entities that users can interact with to access and invoke the programs.

Finally, the applications layer includes the functions embedded into the smart contracts, which depend on the application domain and range from finance to product tracking in agrifood, manufacturing or healthcare industries and showcase the versatility of smart contracts.

3.2.3 Key features of blockchain technology

Building on rapid developments following its popularization as a means to solve long-standing issues in financial applications, blockchain technology is considered one of the most promising solutions to revolutionize information and product management in a variety of industrial sectors. Literature suggests that blockchain adoption could help increase the security, transparency and accountability of supply chains, with substantial benefits, especially in industries dealing with sensitive goods with unique properties, including logistics, healthcare and agrifood (Casino et al., 2019; Dutta et al., 2020; Geetika et al., 2020; Mukherjee et al., 2021). Here, the main applications of blockchain concern product tracking, which is essential to ensure the safety of drugs and foods, monitor storage and transportation, and facilitate the recall of harmful products (Singh et al., 2022; Sunny et al., 2020). In the agrifood industry, product tracking is also important to guarantee provenance and demonstrate compliance with regulations, facilitating market access and providing reliable information to consumers (Kamilaris et al., 2019; Motta et al., 2020). Potential advantages are also related to information management, as the transparency and reliability guaranteed by blockchain-based systems can help reduce transaction times and costs. Furthermore, the absence of a central authority can favour a more equitable sharing of information and value throughout the supply chains. This is particularly important in industries characterized by strong power asymmetries, such as agrifood, where large distribution groups often dictate market prices and impose disadvantageous conditions on small farmers upstream (Brookbanks & Parry, 2022; Glavee-Geo et al., 2022; Pakseresht et al., 2023).

Ultimately, several authors highlight how blockchain-based solutions present four distinctive characteristics, including decentralization, persistency, anonymity, and auditability (Kumar et al., 2020; Wang et al., 2018; Wong et al., 2020). Reflecting on the properties of blockchain-based systems, two key observations can be made. First, the extent to which these features affect the system depends on the type of solution considered. Intuitively, public blockchains, which are potentially accessible to anyone and where all participants hold permissions for data feed, reading, and validation, are markedly more decentralized compared to consortium or private blockchains (Helliar et al., 2020). In contrast, consortium and private blockchains display a higher degree of centralization, due to the authority roles assigned to certain trusted entities and the more selective distribution of data feed and validation rights. Privacy concerns are also relevant due to the limited number of participants, as malicious entities may more easily link transaction data to member identities (Toufaily et al., 2021). At the same time, in these blockchain systems, persistence and auditability are essential to enhance the transparency and accountability of the network compared to traditional solutions.

From this perspective, Wust and Gervais (2018) provide a useful framework to help organizations evaluate whether to adopt blockchain technology, depending on the application requirements and their performance, business and security needs. Ultimately, the authors conclude that adopting a blockchain-based solution is beneficial when multiple entities, who do not fully trust each other, need to interact and update the system state without relying on a trusted third party. A blockchain-based system becomes unnecessary if there is only one actor with permission to issue transactions, as a traditional database offers better performance in such cases, or when a trusted third party is available since this can act as an authority to control participants and transactions. Also, if all participants trust each other, a shared-access database is the optimal choice. However, if writers do not mutually trust each other, a blockchain solution is more suitable. Depending on the need for privacy and auditability, this can be public or private. Lastly, if the writers are unknown, a permissionless blockchain is the ideal solution.

3.3 Theoretical background

In recent years, blockchain technology has been increasingly applied to supply chain management. In the agrifood industry, the adoption of blockchain-based tracking systems enables real-time monitoring of products throughout the supply chain, enhancing safety, transparency, and accountability (Dal Mas et al., 2023; Hasan et al., 2024; Zhao et al., 2019). This is crucial as most agrifood products deteriorate rapidly and are sensitive to changes in environmental parameters such as temperature or light exposure, which could undermine their quality in the passage from production to consumption (Saurabh & Dey, 2021; Vilas-Boas et al., 2023). Furthermore, product tracking is also essential to help agrifood companies demonstrate compliance with the stricter standards that institutions recently enforced to ensure accountability of agrifood supply chains (Kamble et al., 2020; Patelli & Mandrioli, 2020)

These advantages may be particularly felt in the wine industry, which is also affected by serious fraud and counterfeiting issues, and product tracking systems are crucial to safeguard companies and allow consumers to make informed purchasing decisions. Furthermore, the ability to provide reliable information about grape origin and production methods may help wineries implement differentiation strategies, strengthening their brand identity and increasing margins (Carbone et al., 2023; Le et al., 2023). On this note, Bandieri and Castellini (2023) explore the impact of different strategic orientations on the performance of Italian wineries, showing how the most successful companies adopt a differentiation strategy. Similarly, Del Rey and Loose (2023) highlight that the growth of the global wine market is driven by premiumization, reinforcing the importance of differentiation strategies.

As for the crucial role that blockchain technology may play in the wine industry, Malisic et al. (2023) note how the development of global wine value chains has emphasized the role that blockchain can play in ensuring traceability and safety. Adamashvili et al. (2021) used an agent-based simulation model to show how blockchain adoption can help wine companies not only improve traceability but also assists detection of potentially harmful products. At the same time, recent studies suggest that blockchain adoption entails significant managerial and organizational challenges.

Among these, Luzzani et al. (2021) show how the majority of companies have only basic knowledge of blockchain. Interestingly, this holds even for wineries possessing a sustainability certification, suggesting that companies are not yet thinking of blockchain as a means to complement certification mechanisms. Furthermore, in their analysis of traceability systems in the Italian agrifood industry, Corallo et al. (2020) confirm that Italian agrifood companies are interested in traceability issues, but are not aware of the profound connections between digital technologies and product tracking systems.

Danese et al. (2021) investigate whether blockchain-based tracking systems can effectively overcome the limitations of existing counterfeiting measures in the wine industry. The authors focus on how different design choices influence the level of counterfeiting protection guaranteed by specific blockchain solutions. Results show that the level of protection obtained depends on the information feeding and reeding processes and that companies may design such mechanisms to balance costs and safety targets. In general, more frequent updates and timely controls increase the level of protection, to the detriment of complexity and costs. Thus, companies offering low-priced wines may choose to implement limited protection mechanisms and focus on preventing consumers from assuming that low prices entail a low-quality product. On the opposite side, companies producing high-end wines may adopt tighter protection mechanisms to enhance company reputation and leverage the unique qualities of their products on the market.

Overall, several theories and conceptual models have been used to analyse the challenges and opportunities of adopting blockchain systems in the wine industry.

Galati et al. (2021) and Silvestri et al. (2023) move from the Resource Based View (RBV) to analyse the enablers of blockchain technology adoption in the wine industry. Both studies investigate how the development of knowledge and capabilities may help wine companies gain a competitive advantage from the use of blockchain-based tracking systems. In this, both studies combine the RBV with the theory of dynamic capabilities, stressing how the adoption of disruptive technology such as blockchain requires wineries to change their knowledge acquisition and management processes. Results suggest that one of the main challenges of blockchain adoption is wineries' lack of technological skills. However, while Galati et al. (2021) emphasize the role of management in bridging such knowledge gaps and suggest that wine companies can effectively delegate key innovation activities to technology providers, Silvestri et al. (2023) propose that targeted hiring and partnerships with tech companies can help wineries develop the capabilities required to integrate blockchain technology into the business internally. Interestingly, the study also proposes that the adoption of blockchain solutions may be favoured by vertical integration processes. As for the ability to gain competitive advantages, Galati et al. (2021) suggest that the adoption of blockchain systems does not lead to direct savings, but can effectively enhance brand identity and wineries' marketing efforts. Silvestri et al. (2023) instead propose that blockchain helps firms control processes and information flows. In addition to favouring vertical integration of the supply chain, this helps firms to ensure security, transparency and accountability of the supply chain.

On a different note, Tiscini et al. (2020) investigate the implications of blockchain adoption on business model sustainability in the agrifood industry focusing on an exemplary case in the wine sector. The authors refer to the Value Triangle Business Model Canvas (VT BMC) framework, a conceptual model expressly designed to consider the sustainability aspects underlying a business model. Results suggest that blockchain adoption can help wineries improve their value proposition by providing reliable information to consumers. In turn, this can push consumers to promote sustainability practices throughout the supply chain. Furthermore, increased transparency of the supply chain allowed the company to define customers' education initiatives, aimed at increasing consumer awareness of product features. At the same time, the introduction of blockchain entailed set-up costs due to staff training and the need to update information systems. However, these could be offset by improved efficiency in business transactions and simplified accounting and reporting activities.

Tackling the problem from a broader perspective, Cordeiro and Olsen (2021) provide an empirical assessment of the effectiveness of blockchain adoption as an anti-counterfeiting and traceability tool in the wine industry. Referring to the UTAUT theory, the study identifies key factors for technology acceptance, including perceived usefulness and ease of use. Results suggest that companies expect blockchain to significantly influence the development of the wine industry, although reservations regarding set-up costs and efficiency remain. Additionally, producers seem concerned about the time and knowledge needed to adopt the technology, while traders' perspective is more nuanced and depends significantly on the local and international business environment.

Brookbanks and Parry (2022) investigate how blockchain-based platforms might affect trust and trust-building processes in buyer-supplier relationships in wine supply chains. The authors show that blockchain does not remove the need to develop trust-based relationships between partners and perform physical controls on products. At the same time, the use of a shared blockchain platform helps to reduce information asymmetry, duplication of information, and errors caused by the management of chapter documents.

Overall, available literature suggests that blockchain technology could play an important role in the development of the wine industry, increasing security, and transparency and favouring the establishment of trust relationships with partners and consumers. At the same time, several challenges remain and the full implications of blockchain adoption remain unclear. In an exploratory study on the impact of blockchain technology on the sustainability of companies in the wine industry, Luzzani et al. (2021) show that wineries' familiarity with blockchain remains limited and that only a marginal share of companies is willing to invest in blockchain systems in the coming years. Kang et al. (2023) developed a Stackelberg Game model to evaluate the impact that a blockchain product tracking system could have on wine supply chains. Comparing different equilibrium conditions, the authors conclude that the implementation of a blockchain system leads to an increase in wine prices depending on consumers' traceability preferences and privacy concerns.

Indeed, most studies investigating blockchain adoption in the wine industry empirically focus either on limited applications, or isolated success cases. Thus, the requirements necessary for a blockchain system to meet wine companies’ needs are currently under-investigated. In this study, we move from previous literature results and try to gain a deeper understanding of the mechanisms and implications of blockchain adoption in the wine industry, by analysing the perception of companies in the Italian wine industry.

3.4 Methodology

3.4.1 Research design

This study aims to provide empirical evidence of the drivers and requirements of blockchain adoption in the wine industry, using a multiple-case study approach. Case studies are particularly suited for exploratory research, especially when analysing emerging phenomena for which no established theoretical framework is available (Yin, 2018). From this perspective, case studies enable the empirical investigation of the key factors driving a phenomenon, even in the absence of established measurement models that would allow for quantitative analysis (Yin, 2018). Indeed, the nascent literature on blockchain adoption in the wine industry effectively resorted to the case study approach, as the novelty of the phenomenon and the limited diffusion of blockchain make quantitative analysis impractical (Brookbanks & Parry, 2022; Danese et al., 2021).

This is also appropriate due to the prevalence of SMEs and micro-enterprises, which navigate a delicate balance between traditional business models and the push for technological innovation driven by the evolving needs of stakeholders. In this, case studies allow us to grasp nuances in companies' perceptions, enabling the representation of complex phenomena. Specifically, in this study, we opted for a multiple-case study approach to advance the literature and provide a novel perspective. Indeed, multiple case studies allow for the consideration of multiple sources of evidence and enable cross-case analysis, which enhances the reliability of the results and allows for addressing multiple explanations (Yin, 2018). Furthermore, in analysing each case, we opted for a holistic design. Holistic case studies focus on a single unit of analysis. This is appropriate when it is not possible to identify relevant sub-units of analysis (Yin, 2018). We chose to adopt a holistic design as we focus our attention on SMEs, which can be considered single business units.

Consistent with the case study design, we adopt a theoretical sampling technique. Different from statistical sampling, this is effective when the number of observations is limited. Also, theoretical sampling is based on a replication logic aimed at increasing the consistency of the results (Yin, 2018). For data analysis, we use an abductive approach. This means conducting case studies moving from an initial understanding of the theory. This allows to identification of key themes while highlighting novel results (Johansson, 2007; Jonas et al., 2018). Figure 3.1 summarizes the key features and steps of our research. The subsequent sections provide more details on data collection and data analysis procedures respectively.

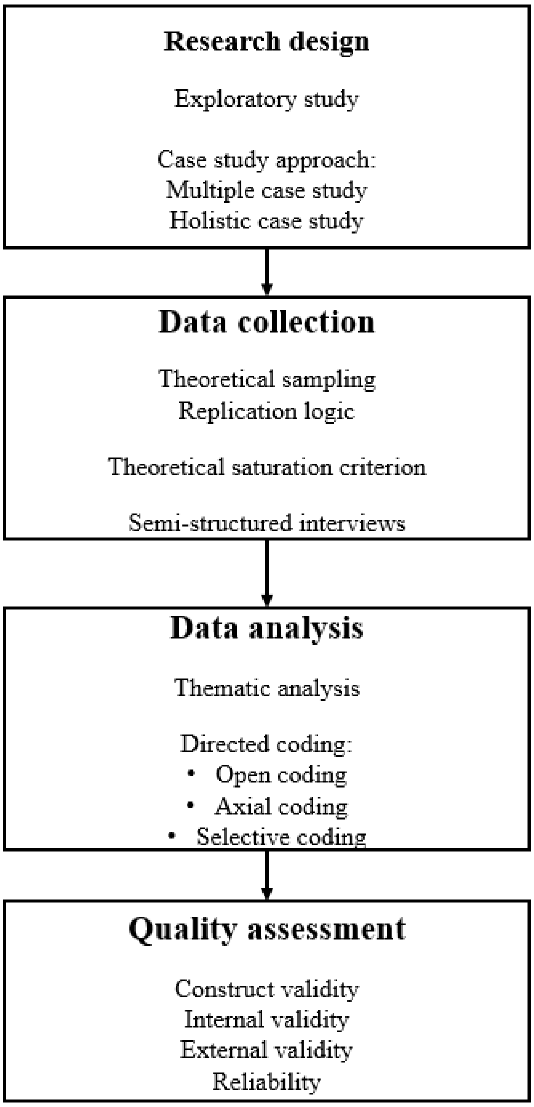


Figure 3.1 research design and methodology.

3.4.2 Data collection

The preliminary step of data collection is the identification of data sources, which requires the definition of appropriate case selection criteria (Dul & Hak, 2008). Thus, we chose to focus on the Italian wine industry, which is among the most relevant globally and is characterized by the variety of its products, which range from low-priced to high-end wines (Bandieri & Castellini, 2023; Luzzani et al., 2021). This makes the Italian wine industry the ideal scenario to investigate the nuances and complexities entailed in the development of blockchain solutions. Second, we chose to focus on SMEs, which represent the majority of Italian wine companies (Bandinelli et al., 2020), and thus allow us to better analyse the current situation regarding companies' perception of blockchain technology. It is important to note that we chose not to focus solely on companies already using blockchain systems, for two main reasons. First, the literature already offers authoritative studies analysing exemplary cases of blockchain adoption in the Italian wine industry (Silvestri et al., 2023; Tiscini et al., 2020). Second, our objective was precisely to move beyond the analysis of these exceptional cases and provide a more realistic representation of the overall state of blockchain adoption in the Italian wine industry. To this end, we gathered and analysed the perceptions of Italian companies regarding the challenges and opportunities associated with adopting advanced tracking systems.

To ensure that the selected companies met these criteria, we moved from a database of Italian wine companies identified by the ATECO code. This is an identifier assigned by the Italian government to classify companies by industrial sector. Then, we distinguished between SMEs and larger companies by considering the information on the revenues and number of employees if available. Next, we chose to consider only companies possessing an active website and e-commerce service, aiming to select firms with a good level of familiarity with digital technologies. Subsequently, we selected only companies producing at least one certified wine, trying to include firms deeply invested in product traceability issues. Finally, we reached out to the remaining companies via email, explaining the objectives of the study and proceeding with those who agreed to take part in the investigation.

Following Dul and Hak (2008) suggestions, we provide multiple sources of evidence, to highlight patterns, create chains of inferences, and generalize findings.

Operationally, we adopted the criterion of theoretical saturation, stopping when the analysis of subsequent cases did not provide new elements (Pinarello et al., 2022). Ultimately, we analysed 16 cases. We collected information by performing a semi-structured interview with a manager from each of the selected companies. These allow the researcher to focus the analysis on key themes while allowing the interviewee to introduce new elements of debate (Jonas et al., 2018). The interviews were conducted between May and July 2023. Each interview lasted approximately 45 minutes and was structured as follows. An introductory part, aimed at collecting information on the organization, the business model, and the core activities. The second part focused on the analysis of regulations, standards, and traceability in the wine industry. The final part focused on blockchain applications, possible advantages, and challenges. We deemed it sufficient to conduct a single interview for each company, as due to the small size of the companies, the management proved to possess a holistic view of the company's characteristics, objectives, and strategies, representing the most authoritative and reliable source of information available. To ensure data triangulation and complement managers' insights, we also gathered information from the companies' websites and any available documents. Specifically, we analysed the websites and official documents in search of information regarding the use of blockchain technology, the companies' stance on traceability issues, certified products, and certification processes, in line with the topics discussed during the interviews.

3.4.3 Data analysis and quality assessment

Data were analysed using thematic analysis. This qualitative methodology is particularly useful for performing cross-case comparisons, highlighting similarities and enabling pattern matching (Quintão et al., 2020). Subject to the interviewee's consent, each interview was recorded and transcribed. This resulted in a 94-page document, used as a starting point for the coding activity. In this, we followed the three-step process suggested by Corbin & Strauss (1990). In the first step of open coding, we carefully scanned the transcript of the interviews to assign first-level codes. These are descriptive labels, useful to highlight key passages of the text. In the second step of axial coding, we merged codes establishing logical connections, to define categories. These are units of analysis characterized by a higher level of abstraction and are the first step that leads to the identification of themes. Finally, in the third step of selective coding, we refined the categories to identify patterns and create chains of evidence leading to theory testing. To ensure reliability, two researchers independently performed the coding activity, moving from a shared understanding of previous literature. Then, a third researcher acted as a mediator to help reach an agreement on the definition of the main themes and explanations.

We conclude this section by providing some information on the criteria we considered to guarantee the robustness and replicability of the results. We refer to the four main criteria illustrated by Yin (2018) and discussed in numerous relevant studies (Gibbert et al., 2008; Quintão et al., 2020; Riege, 2003). Construct validity evaluates how accurately the results of a case study answer the research questions. To ensure construct validity we resorted to data triangulation, i.e., using multiple sources of evidence. Next, we used coding to extract key themes and create chains of evidence. Finally, we asked respondents to review their answers and provide feedback or clarifications.

Internal validity considers the strength of the causal relationships allowing the researchers to make inferences. To enhance internal validity, we first performed within-case analysis and then moved to cross-case analyses to identify patterns and make logical inferences. External validity concerns the extent to which the results of a case study can be generalized to similar contexts.

We addressed this issue by adopting a multiple-case study approach and by following a replication logic in the selection of cases. Finally, reliability considers the consistency and replicability of the findings with respect to the research questions. We aimed to achieve reliability by following a strict case study protocol, and by performing a rigorous coding activity.

3.5 Results

3.5.1 Descriptive analysis

The selected companies produce between 18.000 and 230.000 bottles annually, and perform all production activities, from grape cultivation to bottling, internally. Each company produces at least one wine with IGP, DOC, or DOCG certification. Additionally, five companies hold organic certification, confirming the importance of product traceability, both to meet regulatory requirements and as a marketing tool. The permanent workforce ranges from 4 to 30 employees, with up to 15 temporary workers hired during peak periods, such as harvest season. The owners also act as general managers, shaping the company's strategy and value proposition, while frequently overseeing key production processes themselves. Alternatively, each company employs a production manager responsible for supervising the transformation process, as well as an oenologist. Furthermore, all the companies hired a sales manager, who handles social media and customer relations, indicating an awareness of market trends and a willingness to strengthen customer relationships. Notably, firms are utilizing new sales and communication channels, including digital platforms, while focusing on high-quality wines with unique features and actively promoting their brand identity.

The companies are distributed across Italy: 5 are based in Northern Italy, 3 in the central region, and 8 in the South. Interestingly, even if only one company, located in the South, currently uses a blockchain tracking system, overall knowledge of the technology appears to be higher among the companies in the North. Finally, only three respondents were women, despite women being part of the management teams in nearly all the companies. Table A.2, in the appendix, provides information for each respondent. The names of the companies are indicated only for those who provided consent.

3.5.2 Thematic analysis

In this section, we present the results of the thematic analysis, which led to the identification of eight main themes regarding blockchain adoption in the wine industry. These findings support and expand previous literature results and enable the definition of the key requirements necessary for the development of a blockchain-based system that meets the needs of SMEs in the wine industry. In introducing the main themes relevant to the adoption of blockchain technology, we begin by framing companies' perception of blockchain within the broader context of technological innovation management within the companies. From this perspective, the first theme to emerge is the limited familiarity of companies with blockchain technology. Indeed, among the 16 companies interviewed, only 5 had a clear understanding of the technology and its potential applications for product tracking in the wine industry. Furthermore, only one company currently uses a blockchain-based tracking system, while the other 4 only searched for information, scouting the market in the hypothesis of a future investment. As for the remaining 11 companies, their knowledge of blockchain varies, as some companies show relative awareness of technological developments, while others claim to have only basic information. Consistently, we notice a strong difference in perception between the company that adopted a blockchain-based solution and the others. The manager of the company that uses blockchain states: "*[blockchain adoption] was a fundamental step, to improve business performance and provide guarantees to customers*". On the contrary, scepticism remains among other companies, as witnessed by one of the managers who explains: "*I've heard about it, it's certainly interesting but we need to understand what advantages it can bring or if it's just a temporary trend*".

In investigating the reasons behind this scepticism and companies' limited understanding of blockchain, we introduce the next theme, concerning the lack of technological skills. Results show that one of the shortcomings of wineries is the lack of advanced technological capabilities. Only five companies hired IT or technology specialists, and only two companies have a technology management team. In contrast, all companies pay great attention to aspects related to quality and communication, hiring marketing specialists. This suggests that companies may not consider technological innovation a priority at present. As explained by one of the managers: "*For us, the authenticity of the product is very important [...] even if we use advanced technologies, we make sure to follow the tradition at each step*". On a different note, results highlight the difficulty of companies in hiring qualified personnel. One of the managers complains: "*It is difficult for us to hire, say, an engineer, for two reasons. First, it would be a non-negligible cost, and second, it is difficult to find engineers willing to work in a small* *company in the agrifood industry*". Furthermore, another company explains "*We can't find young people with technical skills willing to work with machinery in the fields*".

Consistently, another key theme concerns costs. Possessing limited resources, SMEs must carefully evaluate investments, and managers' scepticism towards blockchain technology can be partly explained by the difficulty of correctly assessing costs and benefits. As effectively summarized by one of the managers: "*Investing in blockchain technology seems to entail significant costs [...] then we would have to hire qualified personnel and change all our IT systems*". This is a significant obstacle for small wineries, which due to their limited knowledge, could also be underestimating the benefits associated with blockchain implementation. The manager of the company using a blockchain-based traceability system explains: "*It was certainly an important investment, but then we realized that our management costs have significantly decreased [...] previously we wasted a lot of time managing the information, now we have everything available, and the advantages are clear*."

Moving to the fourth main theme, results highlight the over-reliance of companies on management vision and external technology providers as drivers of innovation. The lack of specialists within the company places the responsibility of fostering innovation on the management. Among the companies in the sample, those adopting advanced technological solutions are characterized by the strong determination of the management to pursue innovation goals, as evident from the following quote: "*Product improvement must go hand in hand with technological progress*". However, managers do not always possess the means and foresight to foster technological innovation in the company. It is in this scenario that external technology providers play a pivotal role, offering agrifood companies technological solutions tailored to their needs. As illustrated by one of the companies "*We have an advanced weather monitoring station, which was proposed to us by an external provider [....], and they helped us implement the system and make it work*".

After examining companies' stance on technological innovation and their perception of blockchain technology, we take a step forward and investigate the role that blockchain could play in the wine industry. First, we highlight the importance of digital solutions for supply chain monitoring and control. Companies are deeply concerned with traceability issues and with the need to comply with strict national and international regulations. One of the managers interviewed explains "*Every step is monitored [....], we must provide the government with precise information on the grapes, on the production processes and on what we sell*". Furthermore, given the prevalence of counterfeiting phenomena in the global wine industry, companies feel the need for innovative solutions capable of ensuring transparency and safety.

As emerges from the interviews: "*Unfortunately counterfeiting is a problem in the wine industry and depends on many factors*". In this scenario, digital technologies can offer a solution. The Italian government developed the National Agricultural Information System (SIAN) to monitor and help companies in the wine industry. In essence, the SIAN is a digital platform allowing the government to control wine production. Overall, companies are convinced by the need to use digital technologies to increase transparency and accountability in the wine industry, but at the same time highlight the shortcomings of current solutions. One of the interviewees explains "*The government provides a valid control mechanism, but we need systems that allow us to manage the entire supply chain and also evaluate product performance*".

This passage allows us to introduce two, deeply intertwined, themes. First, the firms observed a recent shift in the market and consumer preferences. This led companies to emphasize marketing and communication. The prevailing opinion among managers is that: "*Consumers have become much more selective, drinking wine has turned into an experience [....] so, we must be able to stand out among the competition*", and more: " [...] *it is important to know how to promote the product, demonstrate its authenticity to consumers*". Consistently, 14 of 16 companies recently hired a marketing or social media specialist to enhance brand identity and customer awareness. As for the second theme, management expresses a strong interest in digital product tracking solutions that can help the company not only monitor the supply chain but also provide new opportunities to interact with the customers. As highlighted by one of the managers: *"It would certainly be useful to have a digital tool allowing us to promote the qualities and tell the story of the products directly to consumers*". Some executives also highlight how this could enable new strategies. Indeed, following market trends, several companies started to focus on the production of high-end local wines. Managers explain that these are less prone to imitation, generate higher margins, and help the company differentiate itself from competitors. At the same time, companies highlight the difficulty of making this type of product known to less experienced consumers. From this perspective, the use of blockchain-based tracking systems could offer SMEs in the wine industry a viable opportunity to make their products known to a larger share of consumers.

In light of the arguments presented so far, we can now introduce the last main theme, which also represents one of the most relevant results of this investigation. Indeed, evidence confirms the great potential for the development of blockchain solutions in the wine industry, from two complementary perspectives. These are the development of blockchain tracking solutions both for supply chain management, and marketing purposes. Overall, the literature seems to consider these aspects as two distinct issues. Our findings suggest instead that SMEs in the wine industry require integrated solutions allowing them to monitor all stages of the supply chain, from production to sales. Specifically, firms need solutions that allow them to increase transparency and accountability of the supply chain, guaranteeing safety, compliance with regulations, and authenticity of products. Thus, SMEs could reconcile supply chain control and marketing objectives, building relationships of trust with governments and consumers. Table 3.1 provides an overview of the main themes.

Table 3.1 overview of the main findings from the thematic analysis. Drivers and challenges of blockchain adoption in the wine industry.

Themes	**Driver/challenge**
Lack of familiarity with blockchain	Challenge
Lack of technological skills	Challenge
High investment costs	Challenge
Reliance on management support and technology providers	Both driver and challenge
Traceability as a supply chain control mechanism	Driver
Change in market and consumer preference	Driver
Traceability as a marketing opportunity	Driver
Blockchain to combine control and marketing goals	Challenge

3.6 Discussion

Following the thematic analysis, in this paragraph we analyse the results in light of previous literature, highlighting elements of continuity, differences, and novel insights. Thus, we leverage the knowledge obtained to identify the requirements that a blockchain-based system must possess to meet the needs of SMEs in the wine industry.

We move from the first theme to emerge from the thematic analysis. Results show that wineries are relatively unfamiliar with blockchain technology. This is consistent with Luzzani et al. (2021) and Corallo et al. (2020) who confirmed that, although Italian wineries are interested in product tracking, they show little familiarity with blockchain and do not perceive the connection between the technology and certification schemes. This leads to the definition of the first requirement, which is the need to increase wineries' familiarity with blockchain technology. From this perspective, government intervention can prove decisive, to foster strategic partnerships between agrifood companies, research institutions, and technology providers.

Moving on, results show that another key element to explain the limited diffusion of blockchain in the wine industry is companies' lack of technological skills. This aligns with previous findings by Silvestri et al. (2023), who stress the need to enhance the technological skills of employees, invest in hiring IT specialists and rethink knowledge creation systems within the firm. In this scenario, we provide an additional element, showing how the development of the technological skills of firms is hampered by the difficulty of attracting qualified human resources. Results show that companies struggle to find both machine operators with good technical skills and technological specialists willing to work for SMEs in the wine industry. Furthermore, companies are discouraged by the high costs of hiring and training human resources. This leads to the identification of a second requirement relating to the need to develop the technological capabilities of SMEs in the wine industry. To this end, government actions are needed to set up training programs and support investments. Furthermore, schools and universities can contribute through the training of new professional figures, combining technological expertise with a focus on the agrifood industry.

The lack of technological skills connects to two relevant issues, namely the attitude of top management towards technological innovation, and the role of technology providers. Results confirm these are two primary drivers of technological innovation for SMEs in the wine industry. Investigating cases of blockchain adoption in wineries, Galati et al. (2021) note the essential contribution of top management in defining objectives and carrying forward the innovation project despite the high costs. In our investigations, we noted a significant difference in attitude between the manager of the company who has chosen to adopt blockchain technology, and the owners of other companies, who are more sceptical and show a stronger attachment to traditional business practices. Thus, the third requirement for the adoption of blockchain technology in the wine industry is the support of top management.

Regarding technology providers, several studies highlight their pivotal role in assisting wineries to set up blockchain-based product tracking systems (Brookbanks & Parry, 2022; Kamilaris et al., 2019). At the same time, papers precisely focusing on examining the dynamics of such partnerships are currently lacking. Also, available literature seems to focus on the advantages provided by these collaborations, while the potential negative effects are often overlooked. Indeed, we argue that, although interaction with external partners can help agrifood companies become familiar with blockchain technology, and fill their skill gaps, over time this can cause a stagnation of companies' technological skills and increase their dependence on external providers. However, the results do not allow us to move beyond this tentative explanation, and we stress the need for future studies on the topic.

The next theme we analyse concerns costs. Literature confirms how high investment costs are one of the major concerns of managers of SMEs in the wine industry when considering investments in blockchain technology (Kang et al., 2023; Saurabh & Dey, 2021). Our findings suggest how this issue may be exacerbated by executives' difficulty in assessing the costs and benefits of blockchain adoption. This is caused by multiple factors, including the company's lack of familiarity with blockchain, low technological skills, and top management scepticism. Thus, we advance that a fundamental requirement for the diffusion of blockchain technology in the wine industry is the development of simple-to-use and low-cost solutions, tailored to the needs of small wineries. Danese et al. (2021) demonstrate that blockchain tracking systems can be designed to balance cost and complexity depending on performance needs, enabling cost-efficient solutions.

After examining the key drivers and challenges of blockchain adoption by SMEs in the wine industry, we may reflect on how product tracking systems affect companies' business models and performance. The literature agrees that the main applications of blockchain in the agrifood industry focus on product tracking. This is particularly relevant for two reasons. First, agrifood products are highly sensitive to environmental factors, which makes them prone to deterioration, affecting quality and threatening consumers' health. Second, the agrifood industry is heavily regulated, with laws and standards aimed at ensuring transparency and accountability.

In this context, blockchain tracking systems can provide a crucial advantage in helping agrifood companies comply with regulations and access the market. This also holds in the wine industry, where blockchain technology could be effectively employed to enhance transparency and support supply chain management (Malisic et al., 2023). The results of this study confirm this thesis, showing how SMEs in the Italian wine industry are invested in product traceability issues and require innovative solutions allowing them to comply with regulations while improving supply chain management. Indeed, factors such as provenance, grape variety, and cultivation methods significantly impact wine pricing and consumer perception. Furthermore, differently from most agrifood products, high-end wines are premium items often produced in limited quantities. This allows wineries to invest in developing a stronger brand identity and enhance their marketing efforts (Carbone et al., 2023). At the same time, this exposes the wine industry to severe counterfeit and label adulteration issues (Casado-Vara et al., 2018; Malisic et al., 2023). Consistently, the results of this study show how SMEs in the Italian wine industry perceived a change in the market and consumer preferences. For this reason, wineries began to execute differentiation strategies, focusing on the unique characteristics of the wines while trying to build stronger relationships with consumers.

Overall, these considerations allow us to introduce the last requirement for the development of an effective blockchain tracking system tailored to the needs of SMEs in the wine industry. Specifically, we argue that issues of traceability as a supply chain control mechanism, and as a marketing opportunity should not be considered separately. Instead, results show how wineries need integrated solutions, capable not only of supporting product tracking in the production phase but also of providing a competitive advantage on the market. Thus, blockchain systems must help businesses comply with regulations, build more secure supply chains, and establish stronger relationships with consumers. Table 3.2 provides an overview of the requirements we identified throughout the discussion.

Finally, figure 3.2 provides an overview of the main findings, and illustrates the connections between drivers, challenges, and requirements of blockchain adoption in the wine industry. Representing opportunities and enablers, drivers also enable the identification of challenges and obstacles to overcome. For example, management support and collaboration with technology providers can play a pivotal role in driving the adoption of blockchain technology but can also lead wineries to over-rely on management vision or the contribution of external partners. Furthermore, this helps explain wineries' lack of familiarity with blockchain technology. The analysis of drivers and challenges allows the identification of key requirements that a blockchain-based tracking system must possess to meet the needs of companies in the wine industry. These include both organizational and technological aspects. For example, the lack of technological capabilities and the unfamiliarity of wineries with blockchain technology leads to the need to raise companies' awareness, overcome dependence on management vision and external knowledge, and foster the development of advanced skills. At the same time, high investment costs and the possibility of combining supply chain control and marketing objectives lead to the need to develop simple-to-use, low-cost blockchain systems, which enable control throughout the supply chain and also offer businesses new ways to interact with customers. Lastly, figure 3.2 connects the requirements to the interventions necessary to develop effective blockchain tracking systems. These invite us to consider the contribution that government institutions can provide and to reflect on the design of modern blockchain solutions.

Table 3.2 overview of the requirements and interventions needed to develop an effective blockchain tracking system for the wine industry.

Requirement	**Interventions**
Need to increase companies' familiarity with blockchain	Partnerships between wineries, research institutions, and technology providers
Need to develop companies' technological skills	Government support to fund training programs and elicit investments Training of new professional figures
Need to develop low-cost blockchain systems	Design blockchain systems balancing complexity, performance, and cost
Need to enable supply chain monitoring and control	Design blockchain systems that help companies comply with regulations and contrast fraud
Need to consider the potential of blockchain traceability systems as marketing tools	Design blockchain systems that help companies market their products and interact with consumers
Need to combine supply chain management and marketing goals	Design blockchain systems that integrate control mechanisms and means to interact with consumers

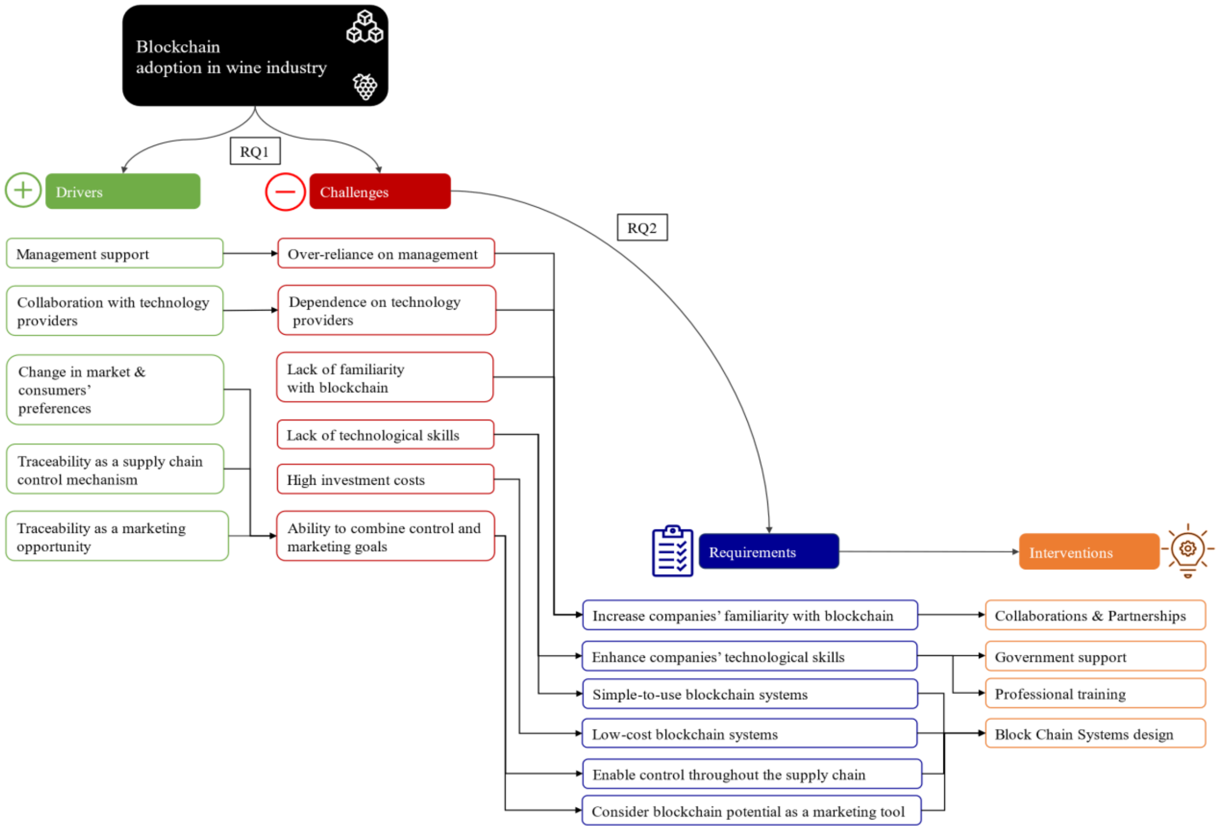


Figure 2.2 drivers, challenges, requirements of blockchain adoption in the wine industry and possible interventions.

3.7 Conclusions

Blockchain is a potentially disruptive technology for innovative product tracking applications in the wine industry. The need to comply with stringent regulations, combat fraud, and the opportunity to strengthen relationships with consumers make the wine industry a particularly relevant scenario for the development of blockchain-based systems. However, the diffusion of blockchain in the wine industry is hindered by several organizational and managerial complexities. Despite this, most of the literature provides only theoretical contributions, focusing on generic agrifood applications (Dal Mas et al., 2023; Patelli & Mandrioli, 2020). Furthermore, most studies highlight technical and regulatory limitations, partly overlooking managerial issues (Feng et al., 2020; Menon & Jain, 2021). Finally, several inquiries focus on large-scale applications, involving big companies and global supply chains (Kshetri, 2018; J. Xu et al., 2020). Thus, only a few studies investigate the role that blockchain technology can play in the wine industry. Among these, some analyse the potential of blockchain tracking systems from a theoretical perspective and a minority focus on the analysis of real cases. While providing valuable contributions, these investigate isolated success stories, which may lead to somewhat biased conclusions, leaving a gap in the literature. This chapter aims to help bridge this gap by providing empirical evidence of the drivers and challenges to the diffusion of blockchain technology in the wine industry. Specifically, the study adopts a multiple case study approach, interviewing the managers of 16 Italian SMEs. Thus, through a rigorous thematic analysis and a three-step coding process, it effectively supports and complements the literature and presents the requirements for the development of blockchain-based tracking solutions that meet wineries' needs.

From a theoretical perspective, this chapter offers two main contributions. First, it moves the literature one step forward by analysing the problem of blockchain adoption in the wine industry using a multiple-case study approach. This allowed cross-case analysis and comparison of multiple sources of evidence, ultimately introducing new relevant elements into the debate. Second, the study offers a novel perspective on the challenges and opportunities of blockchain adoption in the wine industry by avoiding focusing on single success stories and broadening the scope of the study to take into account the perception of companies, representative of the current state of the Italian wine industry. This enabled the identification and analysis of the requirements that a modern blockchain-based system must possess to meet the needs of SMEs in the wine industry.

The results suggest that one of the main obstacles to the diffusion of blockchain is the lack of familiarity with the technology. While valuing supply chain accountability, companies show limited awareness of the potential of blockchain to enhance product tracking. This is exacerbated by several factors, including the lack of technological skills, and the over-reliance of wineries on management support and external technology providers. As for technological skills, the companies stress the difficulty of hiring human resources with advanced technological skills, due to high costs and lack of expert professionals in the sector. As regards the other two factors, results show that the processes of technological innovation in SMEs in the Italian wine industry depend significantly on the vision of top management and collaboration with external providers. This can be a strong driver or a severe hindrance. Managers do not always have the foresight to focus companies' efforts on technological innovation, and it is not guaranteed that partnerships with external providers will provide favourable outcomes. Also, the reliance of Italian wineries on external partners could lead to a stagnation of technological skills. Overall, further studies on the topic are necessary to assess whether these results also hold in different scenarios.

Moving beyond the technological aspects, results suggest that blockchain could play a pivotal role in the wine industry, both as a supply chain control mechanism and as a marketing tool. Indeed, stringent standards require the development of modern digital solutions that help companies monitor the supply chain, track products, and comply with regulations. At the same time, companies may be able to leverage innovative tracking systems to develop new ways to interact with consumers. However, further studies are required to test the validity of these findings in wider contexts, possibly even beyond the wine industry, considering applications in different agrifood sectors.

In terms of practical implications, this study provides institutions, policymakers and companies with useful suggestions to assess the opportunities and challenges of blockchain adoption and to guide the development of blockchain solutions that meet the needs of Italian wineries.

First, to encourage the diffusion of blockchain in the wine industry it is necessary to increase companies' familiarity with the technology. To this end, the creation of strategic partnerships between companies, research institutions and technology providers is crucial. Indeed, companies seem interested in supply chain traceability and transparency issues but struggle to assess the benefits provided by blockchain solutions. At the same time, it is necessary to foster the development of wineries' technological skills. At present, Italian companies struggle to find and hire technology specialists who can drive and manage technological innovation. For this reason, governments must fund training programs and support hiring, while universities may contribute by training new professional figures. Regarding technological issues, a key requirement is the ability of technology providers to develop simple-to-use and low-cost blockchain systems. This is essential to overcome the limited investment capabilities and skill gaps of SMEs.

As for direct actions that firms can take, the results suggest that wineries could benefit from greater technological expertise. Whereas hiring specialists is too costly or impractical, companies could still make an effort to acquire knowledge by collaborating with universities and research centres and attending conferences. Another initiative is to perform a cost-benefit analysis related to the adoption of an advanced product tracking system. Firms should consider how the use of blockchain solutions could affect their business models and marketing activities, playing into global trends in the industry. Indeed, the wine market is experiencing rapid and significant changes, favouring differentiation strategies and requiring companies to enhance their communication efforts. In this, reflecting on the unique features of the products is crucial, as the literature suggests that product tracking is particularly effective in supporting the sales of high-end products and combating counterfeiting and label adulteration phenomena. Finally, results clearly show that companies in the wine industry might be able to leverage product tracking solutions to prove their compliance with regulations and increase supply chain accountability.

Despite the contributions, this chapter is not exempt from limitations. First, this study uses a qualitative approach. This is suitable for exploratory empirical investigations and enables the identification of key themes related to blockchain adoption in the wine industry. Furthermore, the thematic analysis procedure reduces the subjectivity of the analyses and increases reliability. At the same time, future research could focus on larger-scale quantitative studies to consolidate and test the findings. Second, another limitation of this study lies in its exclusive focus on SMEs. While this choice was appropriate given the characteristics of the Italian wine industry, due to the prevalence of small wineries that compete with larger companies by leveraging the unique product qualities, it inevitably restricts the generalizability of the findings. The literature suggests how blockchain-based tracking systems may also be used by large companies and multinationals to ensure product authenticity and safety within global agrifood value chains.

This highlights a limitation in the study, as the opportunities, and even more so, the challenges of blockchain adoption may differ significantly depending on whether small businesses or large enterprises are considered. For instance, large corporations often have greater financial and technological resources, allowing them to invest in customized blockchain solutions and integrate them with existing enterprise systems. Additionally, they may benefit from economies of scale, making the implementation of advanced tracking solutions more cost-effective. On the other hand, large companies operating in global supply chains must deal with increased regulatory complexity and the need to ensure interoperability across multiple stakeholders, which can introduce additional challenges in blockchain adoption.

Conversely, SMEs may be favoured by more agile in decision-making but could also face significant barriers. As seen throughout the chapters, these include limited technological skills, financial constraints, and a higher dependence on external technology providers. These factors may hinder their ability to independently develop and manage blockchain-based systems, making adoption on their part substantially different when compared to larger enterprises. A deeper exploration of these differences, however, goes beyond the scope of this study. Future research should further investigate these dynamics, assessing how firm size influences blockchain adoption processes and the specific challenges faced by different types of businesses within the agrifood industry.

Asa third limitation, this study focuses on the Italian context. This scenario aligns with the scope and objectives of the investigations but also reduces the generalizability of the results, which could change depending on geographical, regulatory or social context. In addition to evaluating the influence of such factors, quantitative analyses are needed to test these findings in cross-national investigations. Finally, this study focuses on the wine industry. While representing one of the most interesting cases for the adoption of blockchain technology, this also limits the scope of the study, as wine supply chains present unique characteristics that influence the analysis. Indeed, high product variety results in different prices and a highly segmented market. Additionally, both large and small wineries coexist, with smaller producers competing by emphasizing product uniqueness to counterbalance economies of scale and brand reputation disadvantages. Counterfeiting is another key issue, particularly for renowned wines, while shifting consumer preferences led to declining volumes and a growing premiumization trend.

Considering other agrifood sectors, both similarities and differences emerge. Most agrifood products are difficult to differentiate, with competition often driven by price rather than uniqueness. As a result, concerns related to counterfeiting and authenticity may be less pronounced, reducing the perceived usefulness of blockchain systems. At the same time, many agrifood products are highly perishable, being sensitive to parameters such as temperature and humidity, and have a relatively short shelf life. In these instances, blockchain-enhanced traceability could be particularly valuable, not necessarily to influence consumer purchasing decisions but rather to ensure optimal storage and transportation conditions throughout the supply chain. Some product categories, however, may share greater similarities with wine and thus represent particularly interesting cases for research. Organic products, for instance, rely heavily on trust in production methods and certification, making traceability especially relevant. Investigating blockchain adoption in these contexts could provide further insights into how the technology can support quality assurance and market positioning across different agrifood sectors.

CHAPTER IV – Developing a Blockchain-based Tracking Systems for SMEs in the Wine Industry: Features, Architecture, and Demonstration.

Summary

This chapter aims to contribute to the existing literature on blockchain technology in the agrifood sector by building on the findings of the previous chapter and providing a demonstration of how to develop an effective blockchain-based solution for the Italian wine industry. Despite growing interest in blockchain applications, few studies focus on how unique industry dynamics and requirements should be considered when investigating blockchain adoption in supply chain applications. This chapter addresses this gap by presenting a detailed analysis of a blockchain-based solution designed to enhance product traceability and satisfy business needs in the Italian wine industry. This is relevant for two reasons. First, the wine industry faces significant challenges related to product authenticity and traceability. Second, despite the growing interest in blockchain, its adoption within the Italian wine sector remains limited, which makes it crucial to understand the drivers and challenges to the implementation of such systems. Thus, this chapter describes the main features and architecture of a blockchain-based tracking system and provides demonstration through practical examples. The chapter contributes to the literature by offering insights into the real-world application of blockchain in a specific industry context, providing both theoretical and practical implications for future research and practice. The study also highlights key requirements for the adoption of blockchain technology, including the need to develop simple, cost-efficient solutions, and the need to enable interaction between all the stakeholders in the supply chain. From a practical perspective, this chapter offers valuable suggestions for policymakers and practitioners, focusing on how to foster the development and adoption of blockchain-based solutions in the Italian wine industry.

4.1 Introduction

Blockchain shows great potential for enhancing product tracking within supply chain management applications (Chittipaka et al., 2023; Motta et al., 2020; Treiblmaier, 2018). Combining blockchain-based systems with smart sensors or RFID tags enables the development of IoT systems facilitating the identification and monitoring of product conditions throughout supply chains (Hammi et al., 2018; Reyna et al., 2018). The transparency provided by these systems could yield significant benefits in industries where control, security, and accountability are crucial, including logistics, healthcare, and agrifood sectors (Antonucci et al., 2019; Hughes et al., 2019; Orji et al., 2020; Patelli & Mandrioli, 2020).

In the agrifood industry, blockchain-based tracking systems can help monitor the conditions of food products during transport and storage, which is important as agrifood products are particularly sensitive to environmental parameters such as temperature and humidity (Fu et al., 2020; Kamilaris et al., 2019; Stranieri et al., 2021). This tracking capability allows agrifood companies to ensure the safety and quality of their products, support recall processes when necessary, and prevent harmful products from reaching consumers (Adamashvili et al., 2021; Bumblauskas et al., 2020). Furthermore, in the agrifood sector product tracking is essential to guarantee the provenance of the products and build trust relationships with consumers. Origin is often a distinctive feature of agrifood products and can help companies market their goods effectively while enabling consumers to make informed purchasing decisions (Rogerson & Parry, 2020; Sharma et al., 2023). Due to the stringent controls within agrifood supply chains, transparency and accountability are also essential to help companies access markets and comply with regulations (Menon & Jain, 2021; Sander et al., 2018).

The study presented in chapter three confirms the potential of blockchain systems for product tracking by focusing on the particularly relevant case of the wine industry. Here, the adoption of blockchain-based systems could prove especially effective in reconciling control and marketing needs, due to the unique features of high-end wines and recent shifts in the market. As for the former, the wine industry faces serious counterfeiting and brand adulteration issues, which not only jeopardize product safety but also damage companies' reputations (Cordeiro & Olsen, 2021; David et al., 2022). As for marketing opportunities, tracking is essential to guarantee the origin of grapes and the quality of production methods. This may prove a crucial advantage in the modern wine industry, which is driven by premiumization and a shift in consumer preferences toward unique, high-quality products (Carbone et al., 2023; Cricelli et al., 2024).

Despite the potential advantages and flexibility in numerous supply chain applications, the adoption of blockchain-based tracking systems remains limited, also in the wine industry (Luzzani et al., 2021; Tiscini et al., 2020). This can be attributed to a series of technical limitations that are widely explored in the literature, including throughput, latency, scalability, and privacy issues (Casino et al., 2019; Mohanta et al., 2019; Zheng et al., 2020).

Beyond these known technical issues, the study presented in chapter three of this Thesis reveals several relevant organizational and managerial challenges that so far received less attention. These include limited awareness of blockchain technology among companies, small businesses' reliance on management vision and cooperation with technology providers, difficulties in assessing the costs and benefits of real-world blockchain applications, high investment costs, and a lack of necessary technological capabilities, among other factors. Overall, these limitations hindered the development of successful blockchain applications, even in sectors where innovative product tracking systems could yield substantial benefits for businesses, policymakers, and consumers.

Considering the gap between the potential of blockchain-based product tracking solutions and their limited adoption even in particularly suitable contexts, it is crucial to advance the research by reconciling two key perspectives. On the one hand, it is necessary to leverage existing literature on the drivers and challenges of blockchain adoption in supply chain applications to define the requirements, architecture, and functionalities that a blockchain system must possess to meet companies' demands and provide tangible benefits. On the other, it is essential to analyse how technological trends, unique industry dynamics, and business needs impact the development and implementation of effective blockchain-based tracking systems. This is essential to contrast the theoretical analysis of blockchain technology's potential with the real advantages that currently available solutions may provide in real-world scenarios.

From this perspective, the literature reveals some crucial gaps. Specifically, several studies investigating the impact of blockchain systems on supply chain management address the issue from a purely conceptual standpoint (Ahmed et al., 2022; Kamilaris et al., 2019; Rana et al., 2021). For instance, various authors review the benefits and challenges of blockchain adoption in supply chain management but fail to contrast these findings against real cases (Kumar et al., 2020; Majdalawieh et al., 2021; Wang et al., 2019). Additionally, while some studies focus on specific sectors or applications, key shortcomings persist, as most studies do not progress beyond the conceptual phase of defining architecture and functionalities. These investigations are useful to provide an overview of blockchain applications and outline research trajectories but leave managerial and implementation challenges under-explored (Nuryyev et al., 2020; Singh et al., 2022; Stranieri et al., 2021). Tackling the issue from a different angle, yet displaying similar limitations, some studies do propose blockchain-based product tracking solutions for specific supply chain applications but often focus on overcoming technical issues and demonstrating feasibility, without addressing crucial managerial and organizational challenges (Paul et al., 2021; Sander et al., 2018). Finally, it is worth noting that there are some studies analysing real cases of blockchain adoption in supply chain applications (Motta et al., 2020; Ocheja et al., 2022). However, these studies tend to focus on isolated success stories which, while hinting at the real potential of blockchain for product tracking, emphasize advantages and benefits while overlooking the implications of developing effective solutions for widespread applications.

This chapter aims to help bridge these gaps by proposing an effective blockchain-based solution for real-world scenarios that take into account industry dynamics and business needs. Building on the exemplary case of traceability in the Italian wine industry, this chapter explores how to develop blockchain solutions that meet companies' needs and align with the environment and competitive landscape of specific scenarios. Furthermore, by illustrating the development process and main features of an innovative blockchain solution tailored to the needs of Italian wineries, the chapter offers insights on how to leverage the opportunities and address the challenges of blockchain adoption. This is important to understand how to transfer the theoretical benefits promised by the adoption of blockchain technology into tangible competitive advantages. Consistently, this chapter aims to answer the following research question:

RQ5) What are the strengths, limitations, and requirements for the effective development of blockchain-based tracking systems in the wine industry?

To answer this research question, this chapter analyses the development of a blockchain-based solution specifically tailored to the needs of Italian wine companies. This result was achieved through a collaboration between the author of this thesis and a team of specialists from Euro.Soft s.r.l., who shared their expertise in developing innovative software solutions. This chapter advances previous literature by reconciling a theoretical perspective on blockchain adoption with the analysis of key practical challenges of developing effective blockchain systems. Consistently, this chapter provides important theoretical and practical contributions.

In terms of theoretical implications, this study enriches the literature on the barriers and drivers of blockchain adoption by analysing how to address technological and organizational challenges to develop an effective solution in accordance with industry-specific requirements. By focusing on the case of the Italian wine industry this chapter also explores how to bridge the gap between theoretical advantages and real-world implementation by highlighting the importance of contextual factors in designing blockchain solutions that align with unique market and sector dynamics.

As for practical implications, this study assists companies and technology providers in defining the requirements, architecture, and functionalities of blockchain systems to suit industries with unique traceability, safety and control needs. The findings also provide evidence of the potential of blockchain tracking systems for supply chain management applications, while highlighting open challenges and persistent limitations. These insights may be key in helping companies consider investments in blockchain technology and urge policymakers to define regulatory frameworks and foster the conditions favouring the diffusion of blockchain systems.

The remainder of the chapter is organized as follows. The next section provides an overview of the objectives and phases that enabled the development of an effective blockchain-based tracking system for applications in the Italian wine industry. Next, through a brief yet rigorous overview of the regulatory and technological scenario faced by Italian wineries, the chapter outlines the main challenges and opportunities related to the development of an effective blockchain solution. Then, the functioning and the main features of the solution developed are described in detail through practical examples. Finally, the chapter concludes by reflecting on the strengths, weaknesses and limitations of the proposed solution, outlining future development trajectories, and synthesizing the main theoretical and practical contributions.

4.2 Methodology

After confirming the potential of blockchain-based tracking solutions for the wine industry, the chapter presents the outcomes of a collaboration between the author of this Thesis, who focused on the analysis of industrial blockchain applications, and a team of technology specialists from Euro.Soft s.r.l. This is a leading Italian SME in the development of innovative digital solutions combining a strong focus on software applications with advanced I4.0 technologies, including AI, Big Data, and IoT. The company is certified under ISO 9001:2015 to "design, develop, supply, and support the deployment of innovative software, IT, and remote-control systems," suited to address complex automation, smart production, and information management challenges. With over 20 years of experience, a team of more than 20 specialists, and more than 200 successful projects, Euro.Soft also partnered with major industrial players and public institutions, including the European Space Agency (ESA) and the Italian Space Agency.

The main objective of the collaboration was the development of a prototype of a blockchain-based product tracking system for the wine industry. This is an open issue with relevant sustainability and managerial implications, relating to the security, transparency and accountability of the supply chain. Furthermore, by focusing on the case of blockchain adoption in the Italian wine industry, the collaboration enabled highlighting and addressing key technological and organizational challenges. This enabled a reflection on how to move from theoretical analyses to the definition of requirements and capabilities needed to effectively operationalize blockchain solutions in real-world scenarios. The following sections present in detail the outcomes of the collaboration, which took place between late 2022 and the first half of 2024, and can be ideally divided into 7 key stages.

The first phase involved the definition of the aim and scope of the collaboration and the milestones of the collaboration. In this preliminary phase, the university research group focused on reviewing the scientific literature to map the main applications of blockchain technology in the agrifood industry. Results led to focusing on product tracking solutions and enabled a theoretical analysis of benefits, challenges and opportunities. Euro.Soft specialists, on the other hand, provided an overview of the main technological alternatives for the development of blockchain applications in the agrifood industry, encompassing platforms, tools, programming languages and supporting technologies.

After setting the overarching goals of the collaboration, the second stage entailed identifying a target sector and specific application. To this end, information collected by both groups was shared and discussed, and three main selection criteria were defined. First, it was decided to focus on sectors where product tracking applications show greater potential. These offer ideal scenarios to assess the real impact of blockchain adoption on agrifood supply chains. Second, attention was directed toward applications that present unique challenges and opportunities. This is essential to ground the investigation of blockchain's role in the agrifood industry within a real-world context, allowing consideration of not only the theoretical challenges but also taking into account companies' needs and industry dynamics.

Finally, the team prioritized applications where the adoption of blockchain-based systems could offer the most significant benefits compared to currently available solutions. This enabled a clearer assessment of blockchain's strengths and weaknesses in comparison to potential alternatives. Ultimately, this led to a focus on developing a product tracking system tailored to SMEs in the Italian wine industry, an ideal scenario to explore the potential of blockchain adoption due to its significant opportunities and challenges.

The third phase entailed defining the requirements and key functionalities of the system to be developed. This step was essential to identify the platforms, tools, and resources suited to design the solution. This was carried out by analysing the challenges, drivers, and opportunities associated with blockchain adoption in the Italian wine industry. In this, it was crucial to move

beyond known technical limitations and to also focus on managerial and organizational implications. This broader focus was possible also through an empirical analysis of wineries' perceptions regarding blockchain adoption, the results of which are presented in chapter three. The fourth phase involved analysing the current state of product tracking in the Italian wine industry. This step was essential to understand how Italian wineries currently address traceability issues and to assess the strengths and weaknesses of existing systems. This entailed examining the SIAN, which represents the current standard provided by the Italian government to ensure the traceability of agricultural products, including wine. The results of this analysis are presented in the following paragraph to provide an overview of the regulatory and technological context underlying the collaboration with Euro.Soft. This step was crucial in reconciling the theoretical analysis of blockchain adoption with a pragmatic perspective.
The fifth phase focused on system design. Thus, the architecture, layers, and main layout of the application were defined. The next phase involved the development of the solution, which included software development, coding, and interface creation. Finally, a testing phase was conducted to evaluate the results and provide an overview of the proposed solution through demonstration. This phase culminated in an evaluation of the system's strengths and weaknesses, as well as reflections on persistent limitations and potential future developments. Figure 4.1 illustrates the main phases of the collaboration.

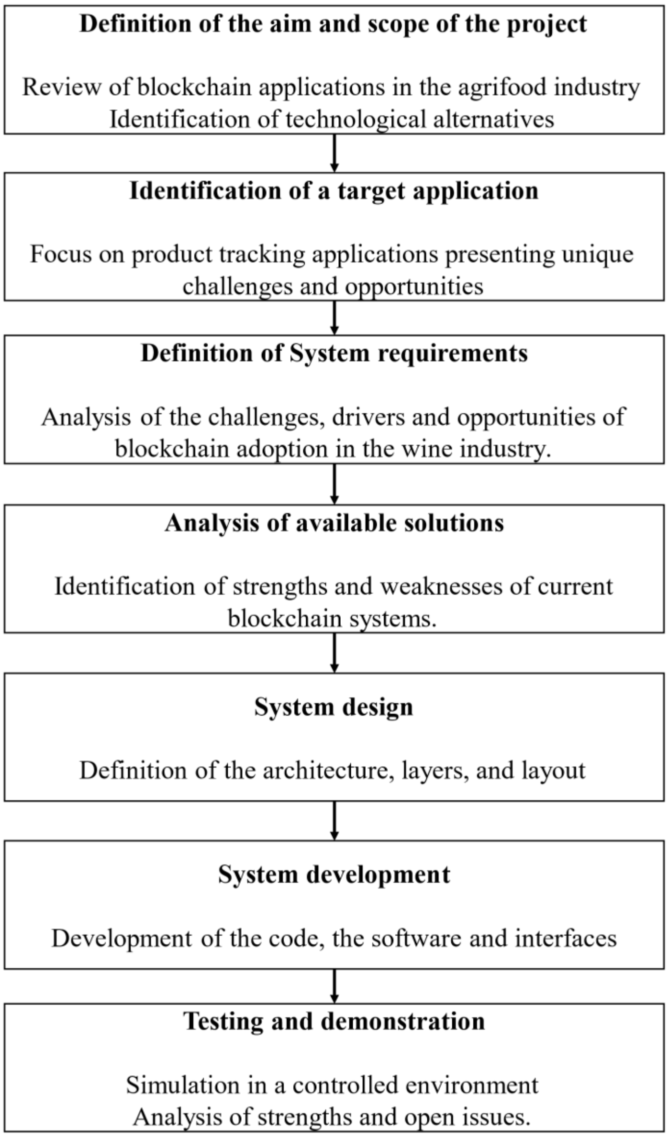


Figure 4.1 key stages of the development of a blockchain tracking system for the Italian wine industry.

4.3 Product tracking in the Italian wine industry

This section provides an overview of SIAN, the digital platform currently used by the Italian government and firms to track agrifood products. The SIAN system is designed to enable product tracking in the agricultural, fishing and livestock industries, and serves as a communication mechanism between the institutions and the companies. In essence, the SIAN has two main purposes. First, it allows the Italian government to monitor national agricultural production and ensure that companies comply with regulations. Second, to support the digitalization of the Italian agri-food industry by providing companies with a platform for product control and tracking. Thus, even if some services are publicly available, most of the information is confidential and the main functionalities are intended for companies, which possess unique credentials and access privileges. The system also features a strong degree of centralization, with the central authority being the Italian government, acting as guarantor and requiring companies to use the system to comply with current regulations regarding the control and safety of agri-food production.

As for the wine sector, Italian law requires firms to upload into the SIAN system information relating to grape cultivation, winemaking processes, inputs used, and outputs obtained. These are used by the government to check that the quantities of grapes are compatible with the output obtained, to verify that the use of additives falls within the legal limits, and to track the quantities and types of products supplied on the market. Thus, reporting activities concern the phases from grape cultivation to bottling, and each actor involved in at least one of these steps is required to upload information on:

- The quantities and varieties of grapes grown or purchased.
- The production process, with an indication of the grapes, additives and their quantities.
- The quantity of output obtained which must be compatible with the inputs used.
- Suppliers and customers, with an indication of the quantities purchased from or sold to each.

Additionally, companies finalising the production processes and performing bottling activities are required to communicate to the government the exact quantity of wine obtained, so that an appointed authority may provide the authorization to label and sell precisely that quantity of product. Overall, the Italian wine industry is highly regulated, and the products are closely tracked from the cultivation to the bottling stage. Figure 4.2 shows the SIAN home page, through which Italian agrifood companies can log in to the system and access reporting functions.

Figure 4.2 SIAN home page.

Despite this, the SIAN system seems to primarily address the need of the Italian government to prevent fraud and monitor companies' activities, rather than being a useful tool enabling firms to enhance the management of product flows or even gain a competitive advantage. Indeed, the SIAN exhibits some key weaknesses. First, the system has no features that enable market analysis or help companies enhance their marketing efforts. The tracking ends with the bottling and does not cover the final stages of distribution and sale. There is no effective system enabling companies to gain direct access to market intel or consumers to access product information. This highlights the lack of an integrated solution combining control and business needs and encourages many companies to adopt additional tools to compensate for the system's shortcomings, resulting in increased costs and complexity. This causes severe redundancy issues, as companies are forced to duplicate information acquisition and management activities. The second weakness is the low transparency and auditability of SIAN. Only the authority appointed by the Italian government to monitor the industry has full access to the information stored in the system. Conversely, companies can only access personal information, and consumers can only view publicly available information. While this helps to ensure privacy and protect the interests of companies, il also reduces the security and accountability of the supply chain, as only the government can perform the necessary control activities.

The third issue relates to the high degree of centralization of the system, which does not enable interaction between companies and does not leverage shared consensus mechanisms. This contributes to increasing information management costs and makes control activities more difficult and expensive.

The fourth limitation concerns the reliability and persistence of information. Unlike blockchain-based solutions, the SIAN system allows companies to modify previously uploaded information provided specific deadlines are met. Furthermore, only the changes made after such deadlines are highlighted by the system. Otherwise, the system only stores the most recent information. This makes controls onerous and complex and increases the risk of tampering and spreading incorrect information throughout the system.

Finally, due to the strong focus on fraudulent practices control and prevention, the SIAN system does not allow access and does not provide any information about products to consumers. As seen in the previous chapter, this is a relevant shortcoming, as modern tracking solutions show great potential as marketing tools. Considering the shift in consumer preferences characterizing the wine industry, the ability to exploit digital solutions to emphasize the qualities of products to customers may represent a key competitive advantage. From this perspective, the combination of blockchain platforms and QR codes on labels could have a disruptive impact on the competition dynamics in the wine industry.

Overall, SIAN appears to function primarily as a prevention and control instrument, intended to assist the government's on-site monitoring activities in combating fraud and counterfeiting, rather than as a tool specifically designed to support the digitalization of the Italian wine industry and respond to wineries' needs. From this perspective, the findings in chapter three present and investigate the requirements that a blockchain tracking system must possess to meet Italian wineries' needs. While SIAN represents an effective control instrument, it lacks core functionalities and features. Moreover, SIAN reveals some structural limitations leading to crucial weaknesses in the management, sharing, and verification of information.

4.4 Blockchain tracking system description

This paragraph outlines the main features of a blockchain-based system designed to support product tracking in the Italian wine industry while balancing costs, complexity, and accessibility. Specifically, the next paragraph offers an overview of the architecture, main features and functionalities of the proposed solution. The following section, instead, provides a demonstration by detailing three key operations, one for each type of actor in the network.

4.4.1 System overview

The system's architecture is composed of five layers. The foundational layer provides the infrastructure, and a reliable execution environment. After evaluating the main available alternatives, we selected the Ethereum blockchain as the reference environment for this prototype. This choice was driven by three key considerations. First, Ethereum is a public blockchain that enables the development and deployment of unique applications. This was a key factor in reducing development costs while ensuring all the fundamental features of blockchain systems, such as immutability, transparency, and decentralized consensus. Second, adopting a public blockchain model is useful to showcase the feasibility of such a solution in the most general conditions, and does not preclude the potential transition to a consortium or private model in the future. Finally, Ethereum's account-based model supports the use of smart contracts and efficient asset management methods, both of which are pivotal to the system's functionality. Regardless, the foundational layer includes Ethereum nodes, each holding an updated view of the information published on the blockchain.

To test the system and demonstrate its feasibility in real-world scenarios, we used the computer program Ganache to simulate the behaviour of an Ethereum node with 10 accounts. In this, each account is assigned 100 Ether, Ethereum's native currency. This is required to invoke the contracts used by the application and to validate the information. We also used the browser plugin MetaMask as a support account management tool. MetaMask allowed us to connect to the simulated node created by Ganache, enabling the execution of basic transactions and testing system functionality in a controlled environment. In practice, Ganache generates a new Ethereum node without prior transactions. Each node is assigned a unique IP address and two keys: a public key, used for account identification, and a private key, which in real-world applications is required to sign transactions securely. Although the Ganache node is static and no transactions occur by default, basic operations such as currency transfers between accounts can be executed using tools like MetaMask. This setup mirrors the foundational capabilities of a blockchain-based system for real-world applications.

The second layer is the contract layer, which presents the code of the smart contract developed for the application. This is written in the programming language Solidity. Once deployed, the smart contract is assigned a unique address, allowing network participants to invoke it to execute transactions, perform data verification, or trigger specific operations.

For this project, the smart contract was developed using the Remix – Ethereum IDE, a tool specifically designed for Ethereum-based applications. Remix enables developers to write and test Solidity code, connect to an Ethereum node (either real or simulated), and deploy the contract to the network.

The third layer is the operations layer, which includes software enabling the connection between the application system, the contract, and the foundational layers. This is essential for sharing information throughout the system, allowing network participants to issue transactions, and access the blockchain ledger. This also includes the backend mechanisms needed to monitor, halt, or update the system.

The fourth layer is the application system layer, which includes a software to manage data that cannot be stored directly on the blockchain, either due to size limitations or privacy concerns. This facilitates interactions with users. It also connects with the contract and foundational layers to enable participants to invoke the smart contracts and access the blockchain ledger.

The final layer is the user application layer and includes the web services and interfaces enabling users to access the system's tracking capabilities using their own terminals, such as PCs or smartphones. It is connected to the application system layer to enable recording and retrieval of information. Finally, it includes software for managing accesses and user accounts, essential to confirm participant identities and provide access permissions. Figure 4.3 depicts the system's architecture, illustrating the connections and exchange of information between the layers.

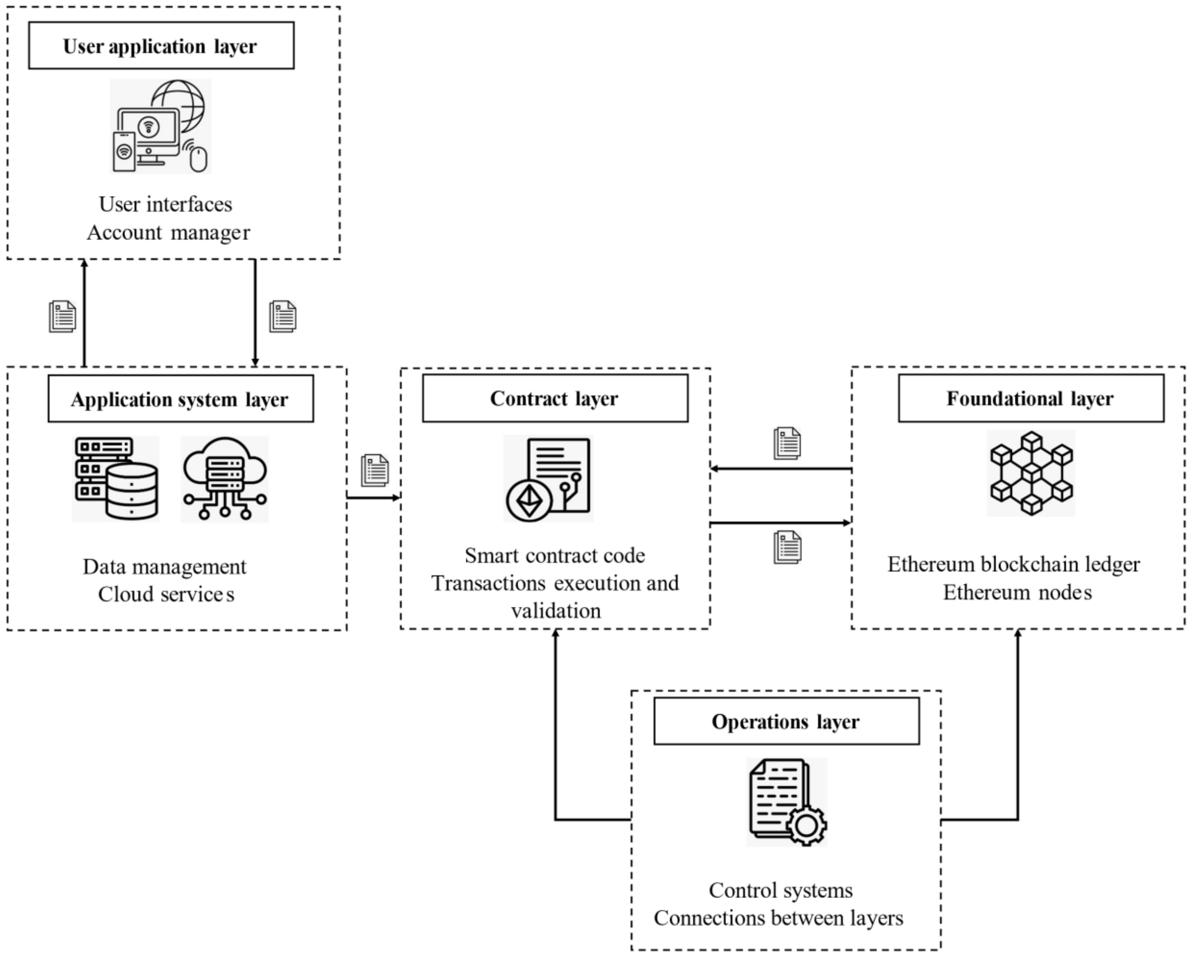


Figure 3.3 system architecture.

For demonstration purposes, the system currently presents three types of actors: grape growers, winemakers, and certifiers. The system allows grape growers to record their production and perform transactions to sell grapes to winemakers. Winemakers may perform several production steps while moving from acquiring the grapes to bottling wine. Certifiers are tasked with receiving certification requests from winemakers, conducting the necessary checks, and assigning certifications to products when applicable.

Overall, the proposed solution ensures comprehensive traceability throughout the supply chain by assigning a unique identification code to each wine batch, which is then recorded on the Ethereum blockchain using the smart contract. This entails three key steps. First, network participants use their accounts to access a web application that interacts with a library of computer programs hosting the smart contract. Next, the library invokes the smart contract, which generates a SHA-256 hash, a cryptographic representation of the batch data. This hash is securely stored on the Ethereum blockchain and indexed with a timestamp. Once recorded on the Ethereum blockchain, this information is publicly accessible. Simultaneously, the timestamp is stored in the platform's backend database, creating a link between the hash, the timestamp, and the batch information. This connection allows both network actors and external users to retrieve the hash associated with a specific batch at any time. External users, such as consumers, just need to be provided with hash information to access reliable information on the products. As several studies suggest, this may also be done via QR codes on products' labels (Chandan et al., 2023; Cordeiro & Olsen, 2021; Köhler & Pizzol, 2020). By comparing the retrieved hash with the current batch information, users can confirm whether the data has remained consistent, ensuring product information has not been manipulated. Moreover, subsequent operations on grapes or batches may reference previous hashes, enabling end-to-end tracking of products across all stages of the supply chain.

It is important to note that only the operation of storing hashes on the blockchain is effectively a transaction, which generates a trace and requires validation before being appended to the blockchain. Executing transactions is costly and requires Gas, a currency used in the Ethereum blockchain. The cost of tracking operations for network participants depends on the frequency and complexity of these transactions. In contrast, information verification is not a transaction, meaning it is free and does not leave a trace on the blockchain. This allows external users, such as consumers, to verify product data for free. However, the system still records hash retrieval requests received by the smart contract, providing supply chain actors with valuable insights. This feature may be useful to help companies assess the system's performance and gain insights into product demand and sales trends. Figure 4.4 shows the key steps required to encrypt product information into a unique hash, the generation of a corresponding timestamp, and the way consumers can use this timestamp to access reliable product information on the Ethereum blockchain.

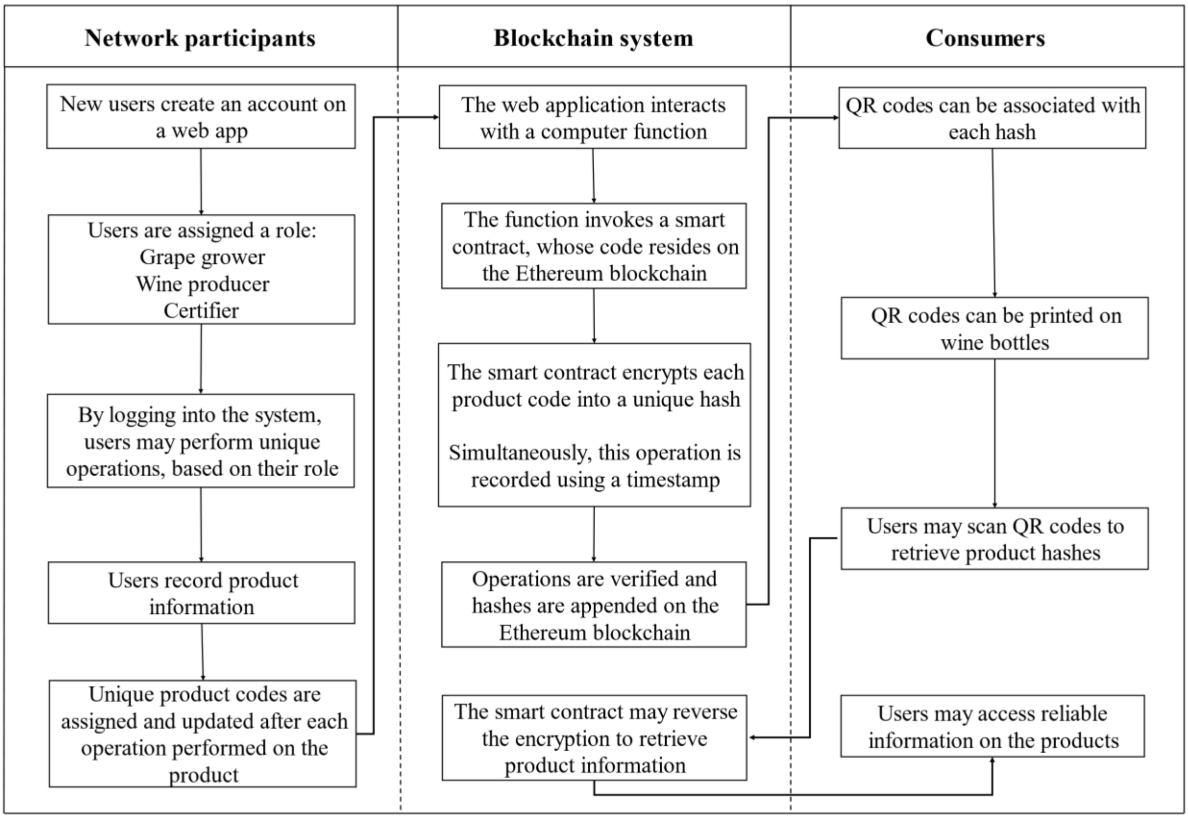


Figure 4.4 flow diagram describing the steps required to record and retrieve product information.

The system effectively connects all the actors in the wine supply chains while ensuring that all key information related to grape cultivation, wine production, and certification is recorded and publicly available. Crucially, the system offers a robust solution for tracking and verifying wine batches while balancing costs and accessibility, thus enabling wineries to reconcile supply chain control and marketing objectives.

4.4.2 Demonstration

The system distinguishes between three types in the network: grape grower, winemaker, and certifier. Each participant may create an account with information about their company and their role in the wine supply chain. Depending on the type of account created, the system provides specific features. For example, the system will allow a grape grower to register their vineyards in the system. To protect the privacy of participants, actors do not have access to information provided by others, but the system checks that the data regarding interactions between actors is consistent. Similar checks are also performed to ensure that the inputs and outputs of the winemaking processes are within law regulations. This helps to control the supply chain and prevent fraud.

Overall, the examples will illustrate how the system facilitates traceability across all critical stages of wine production, from grape cultivation to bottling and certification. The paragraph concludes by showing how all relevant information can be uploaded to the Ethereum blockchain. This is achieved by using a browser service to invoke a smart contract that generates a unique code for each product batch. Then, this information is secured, timestamped and appended to the blockchain. By retrieving the batch's unique identifier, network participants and external users may access the blockchain record to confirm the integrity and authenticity of the information, ensuring a transparent and tamper-proof system for wine production traceability.

The first example shows how a grape grower may register a new vineyard in the system and sell grapes to a winemaker. After logging into its account, the grape grower can access a dedicated function designed for this purpose. Thus, the grower may provide key information about the vineyard, including details such as the location, size, grape variety, and cultivation methods. Figure 4.5 shows the main screen detailing this operation: at the top is the name of the grape growing company, while each line contains information about the vineyard.

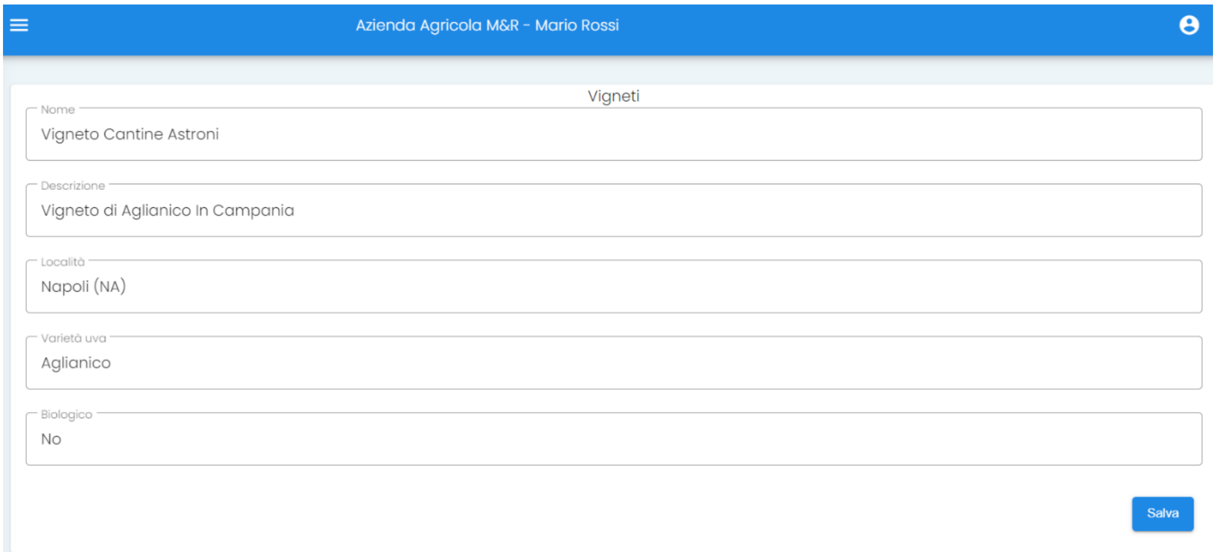


Figure 4.5 registration of a new vineyard.

The second operation illustrates the sale of grapes to a winemaker. The grower enters information regarding the provenance of the grapes, the quantity sold, the buyer, and the date of the operation. The information on the quality of the grapes is derived from the vineyard, and the system automatically performs the necessary checks on the date and quantity of grapes available to the grower to sell. Figure 4.6 details this operation.

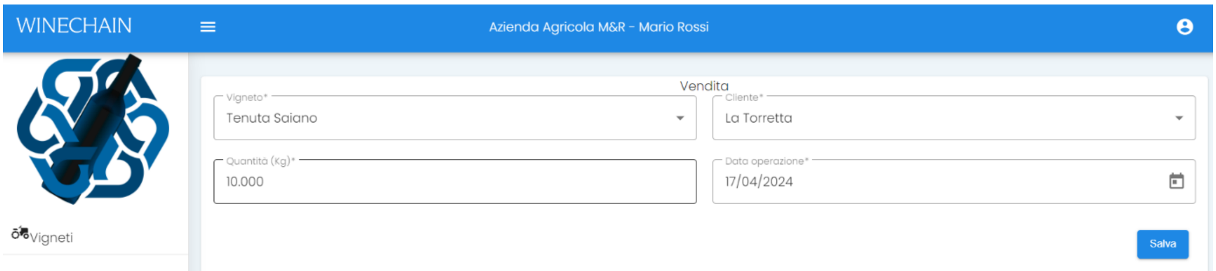


Figure 4.6 sale of grapes to a winemaker.

The next example focuses on the options available to winemakers and shows hot to track products in key stages of the production process, from blending, to bottling, to sending a certification request. The first step involves checking the grapes available. By logging into their account, the winemaker may view a list of purchased grapes. This list, shown in figure 4.7, includes details about the origin of the grapes, the initial quantity purchased, and the quantity currently available. Highlighted grape varieties will be blended to produce a unique wine.

Figure 4.7 purchases and available grapes screen.

Figures 4.8, 4.9, and 4.10 illustrate changes in the system's state related to a new winemaking operation. Specifically, figure 4.8 displays the winemaking processes already completed by the winemaker. Figure 4.9 presents the information that the winemaker must input into the system for a winemaking operation. In this example, the winemaker performs a blending of two grape varieties. The system records details about the provenance of the grapes, the blending process, and the yield of the operation. Notably, the system verifies that the yield is consistent with the quantities of grapes used in the process. Furthermore, the system assigns a unique batch number to the wine produced, ensuring traceability and accurate tracking of the operation's outcome. Figure 4.10 shows the updated winemaking screen, where the newly registered operation is displayed. The quantities of available grapes are also updated accordingly, reflecting the resources used in the process.

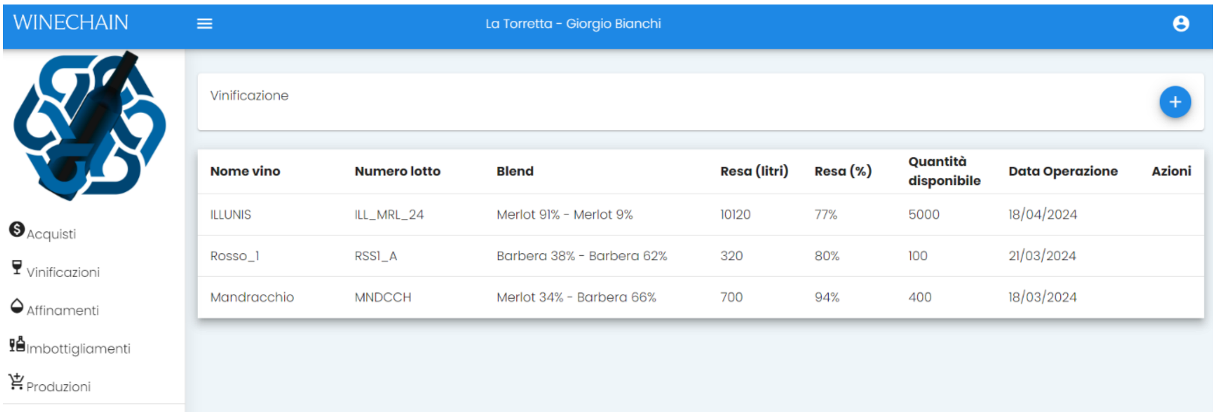


Figure 4.8 previous winemaking operations completed by the winemaker.

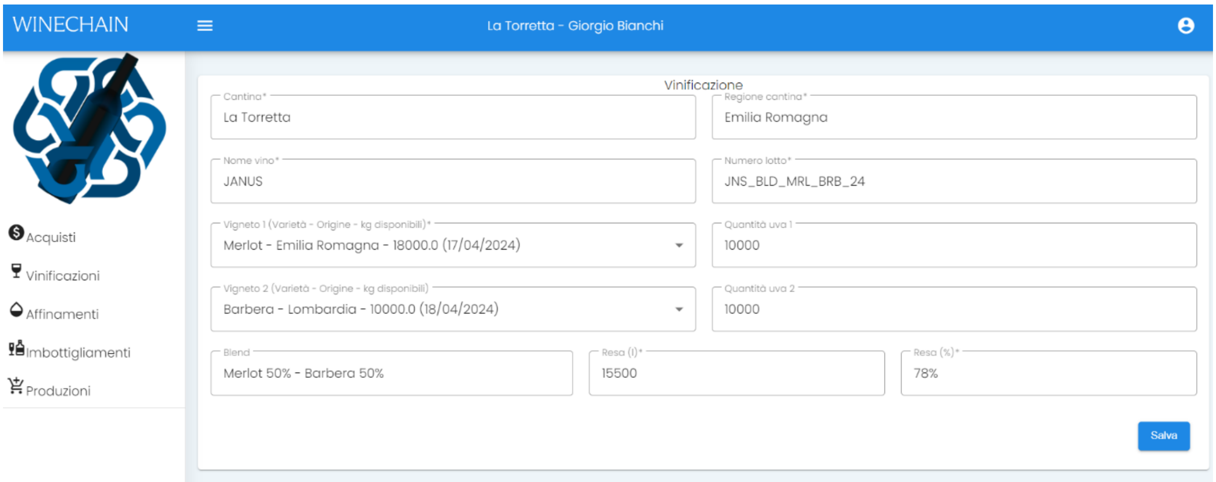


Figure 4.9 key information on the winemaking process.

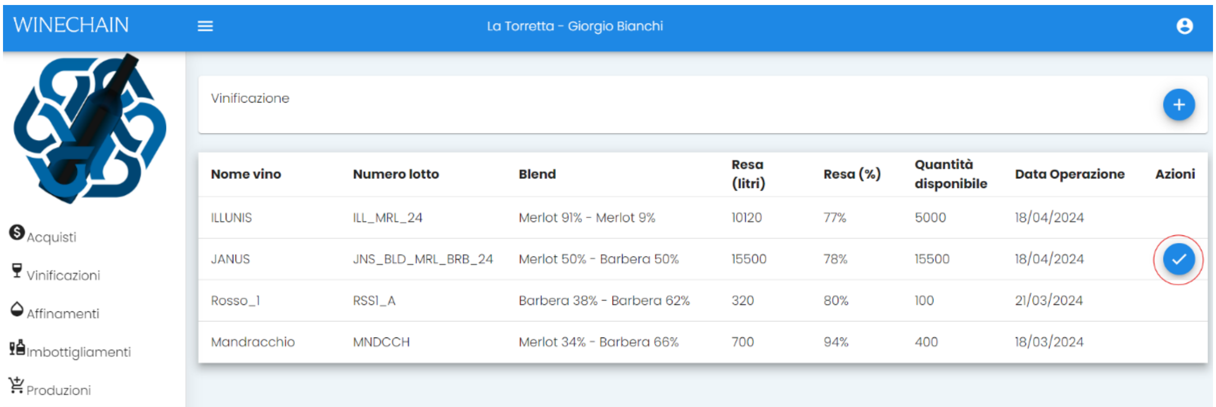


Figure 4.10 updated screen showing the newly registered winemaking operation.

Moving on, figures 4.11, 4.12, and 4.13 illustrate the changes in the system's state related to the bottling operation. Figure 4.11 displays the screen showing previously completed bottling operations. Figure 4.12 presents information related to the bottling process, including the wine type, batch number from previous operations, the bottled quantity, bottle capacity, and process yield. Finally, figure 4.13 shows the updated bottling screen with the newly registered operation.

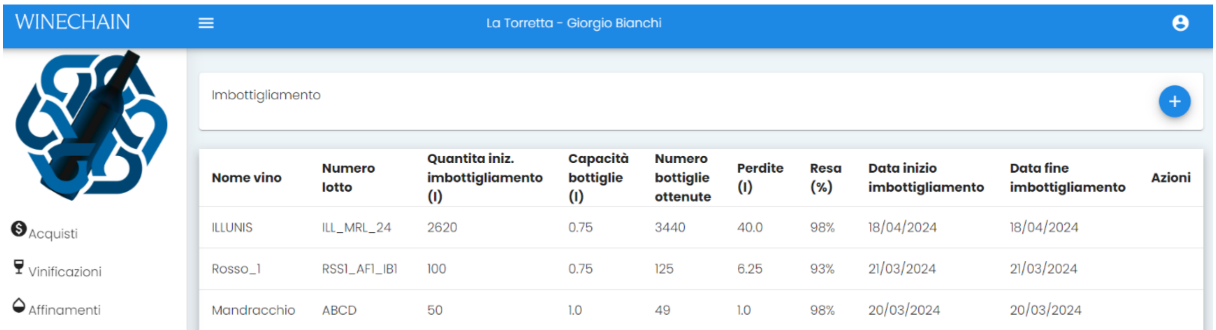


Figure 4.11 previous bottling operations completed by the winemaker.

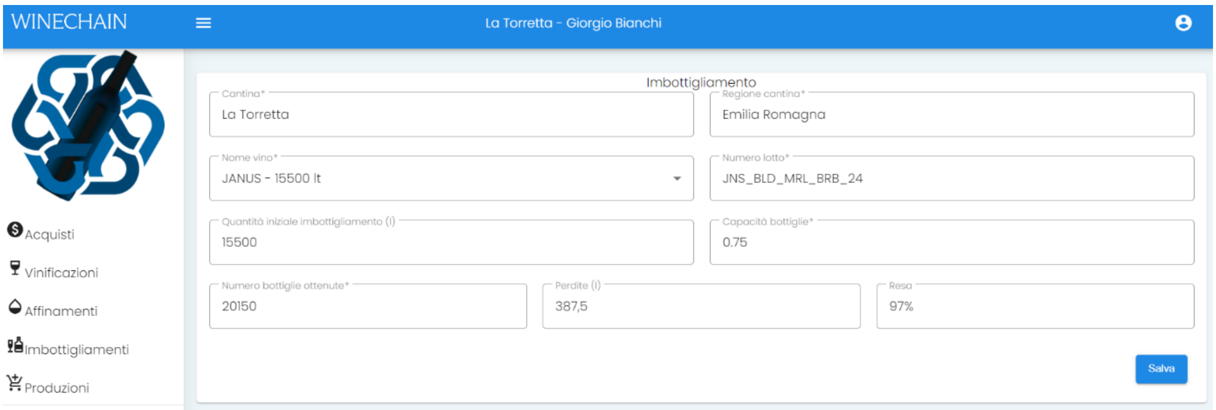
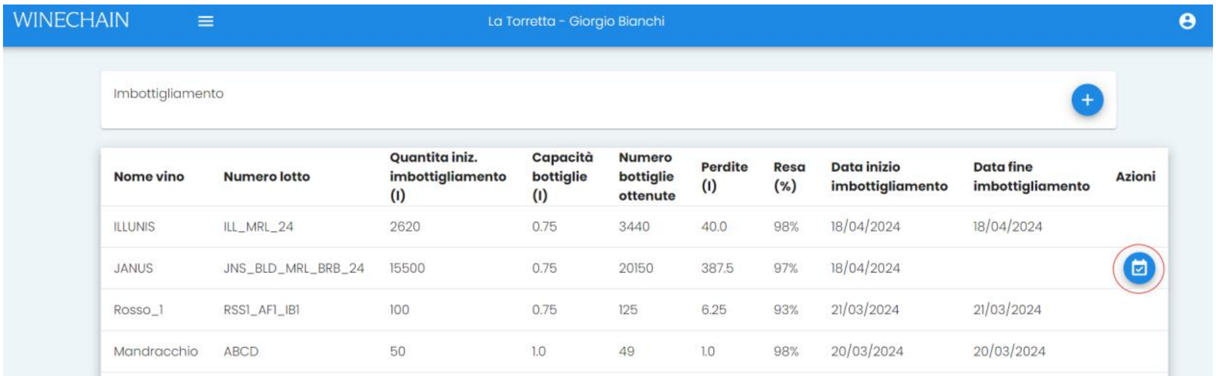


Figure 4.12 key information on the bottling process.



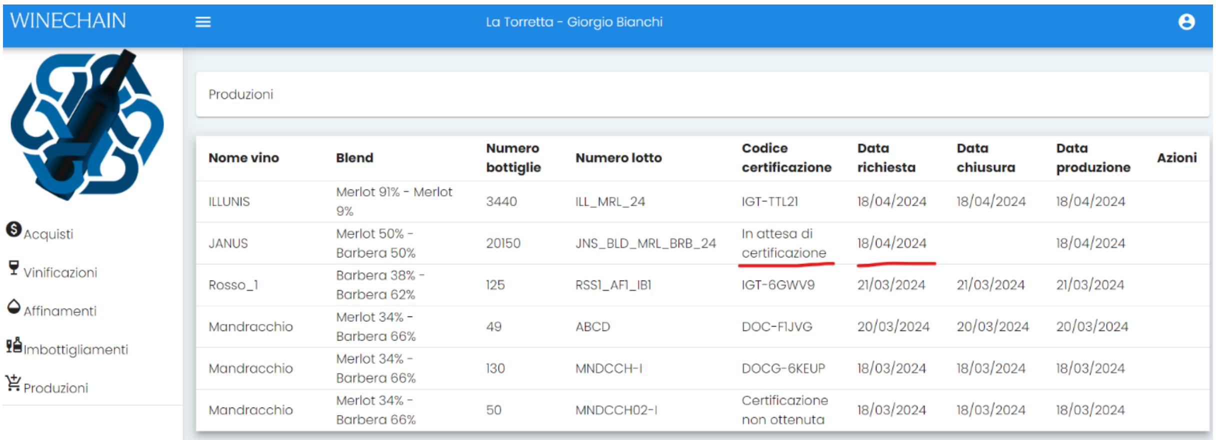
WINECHAIN La Torretta - Giorgio Bianchi

Imbottigliamento

Nome vino	Numero lotto	Quantita iniz. imbottigliamento (l)	Capacità bottiglie (l)	Numero bottiglie ottenute	Perdite (l)	Resa (%)	Data inizio imbottigliamento	Data fine imbottigliamento	Azioni
ILLUNIS	ILL_MRL_24	2620	0.75	3440	40.0	98%	18/04/2024	18/04/2024	
JANUS	JNS_BLD_MRL_BRB_24	15500	0.75	20150	387.5	97%	18/04/2024		
Rosso_1	RSS1_AF1_IB1	100	0.75	125	6.25	93%	21/03/2024	21/03/2024	
Mandracchio	ABCD	50	1.0	49	1.0	98%	20/03/2024	20/03/2024	

Figure 4.13 updated screen showing the newly registered bottling operation.

Finally, figure 4.14 shows the system's state when the winemaker submits a certification request to one of the Italian government-authorized entities. This is an optional operation, available for wines that are eligible for quality certification. The system records the date of the request and displays the message "waiting for certification."



WINECHAIN La Torretta - Giorgio Bianchi

Acquisti
Vinificazioni
Affinamenti
Imbottigliamenti
Produzioni

Produzioni

Nome vino	Blend	Numero bottiglie	Numero lotto	Codice certificazione	Data richiesta	Data chiusura	Data produzione	Azioni
ILLUNIS	Merlot 91% - Merlot 9%	3440	ILL_MRL_24	IGT-TTL21	18/04/2024	18/04/2024	18/04/2024	
JANUS	Merlot 50% - Barbera 50%	20150	JNS_BLD_MRL_BRB_24	In attesa di certificazione	18/04/2024		18/04/2024	
Rosso_1	Barbera 38% - Barbera 62%	125	RSS1_AF1_IB1	IGT-6GWV9	21/03/2024	21/03/2024	21/03/2024	
Mandracchio	Merlot 34% - Barbera 66%	49	ABCD	DOC-FIJVG	20/03/2024	20/03/2024	20/03/2024	
Mandracchio	Merlot 34% - Barbera 66%	130	MNDCCH-I	DOCG-6KEUP	18/03/2024	18/03/2024	18/03/2024	
Mandracchio	Merlot 34% - Barbera 66%	50	MNDCCH02-I	Certificazione non ottenuta	18/03/2024	18/03/2024	18/03/2024	

Figure 4.14 certification request screen.

After the winemaker has sent the request, the attention shifts to the certifier, who can access the system via his account to view and manage the certification requests received from multiple producers. The certifier is tasked to perform physio-chemical analyses on the wine batches to assess coherence with predefined quality and standards. Upon successful outcome, the certifier updates the system with the certification details and assigns a unique ID to the corresponding batch code. This step guarantees that the certification information is securely integrated into the traceability record. Figures 4.15 and 4.16 show the steps of certification selection and code assignment to products.

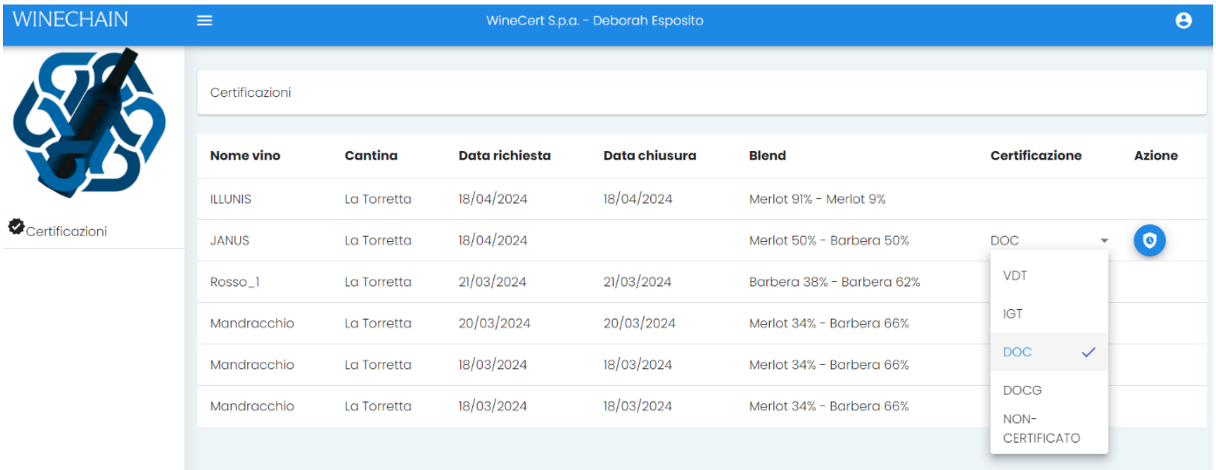


Figure 4.15 certification selection.

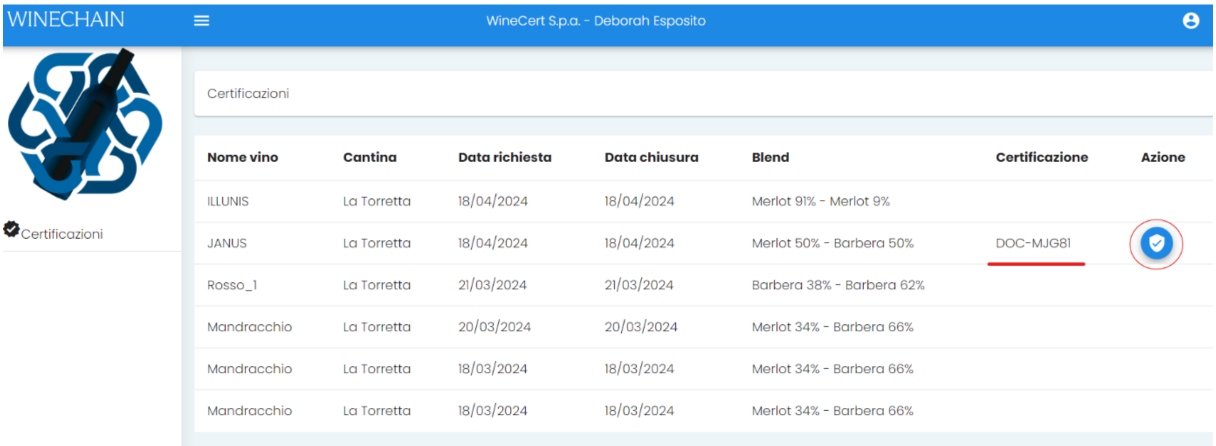


Figure 4.16 assignment of the certification code.

Following the certification procedure, the system notifies the winemaker that the certifier has performed his assessment and that the requested certification has been assigned to the product. Finally, the system presents the winemaker with the option to encode and append the information about the product batch to the Ethereum blockchain. Figure 4.17 shows the option available to the winemaker. This ensures reliable product information throughout the supply chain.

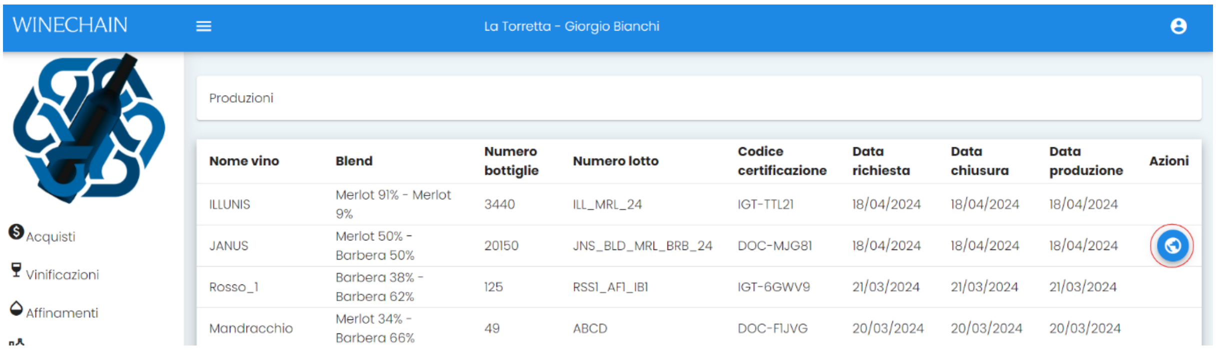


Figure 4.17 confirmation of publication on the blockchain.

Figures 4.18 and 4.19 show the mechanisms used by the system to store and retrieve batch information from the blockchain. Specifically, figure 4.18 shows the hash generated from the batch data and that will be appended to the blockchain. Figure 4.19, on the other hand, illustrates the timestamp associated with the publication of the information on the blockchain, which the smart contract returns as a key for data recovery and verification. Since this is the blockchain transaction operated by the system through the smart contract, this operation has a cost in Gas.

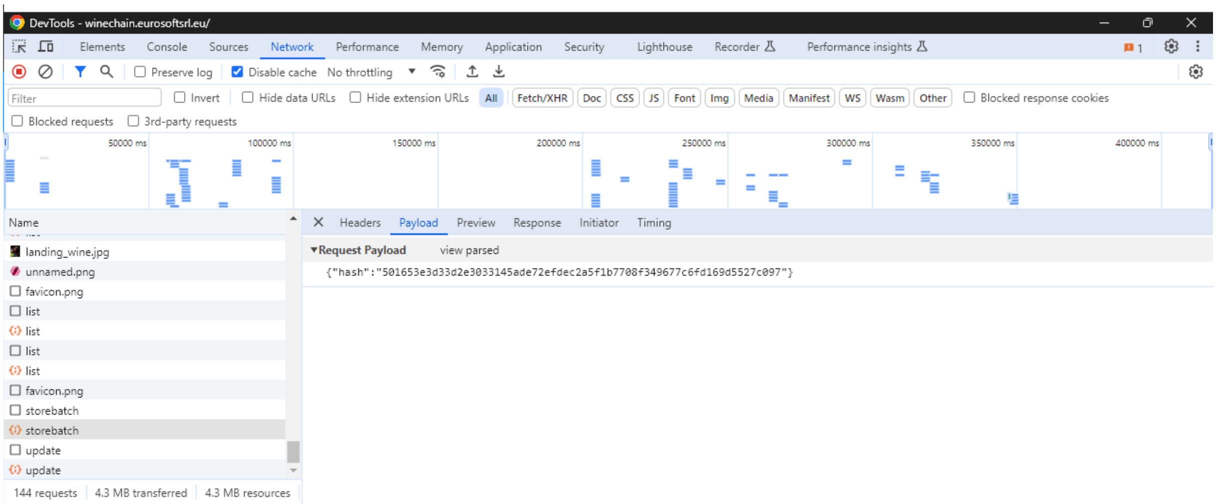


Figure 4.18 generation of the hash associated with the product batch.

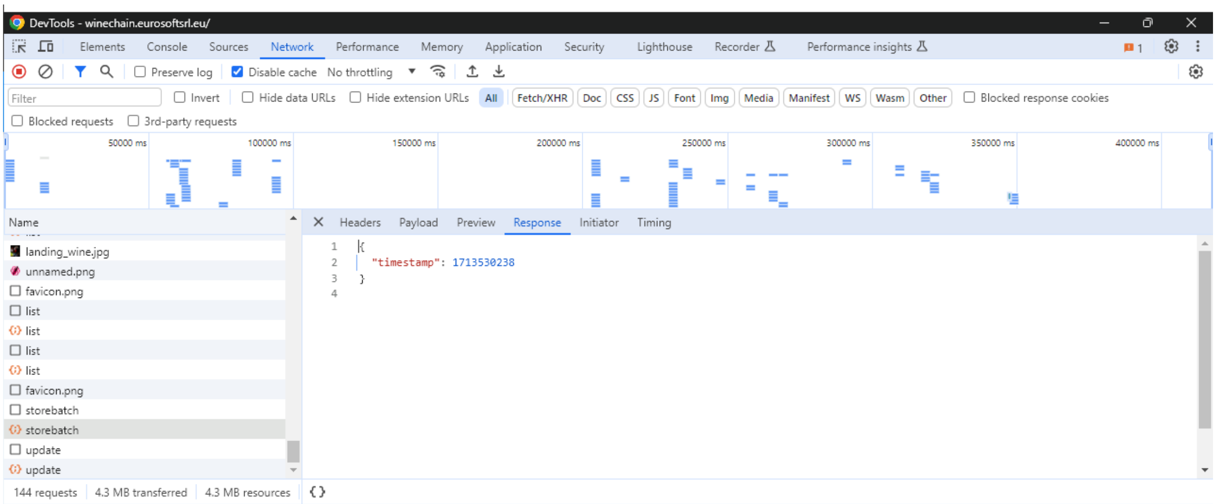


Figure 4.19 generation of the timestamp associated with the recording on the hash on the blockchain.

Figure 4.20 contains the LOG messages of the application that interfaces with the smart contract. The image shows the call to the smart contract, the timestamp returned, which coincides with the value found in the previous image, and the hash of the transaction. Figure 4.21 proves that this hash corresponds to the one present on the public blockchain, an environment simulated through the "Ganache" software.

Figure 4.20 call to the smart contract and returned timestamp and hash.

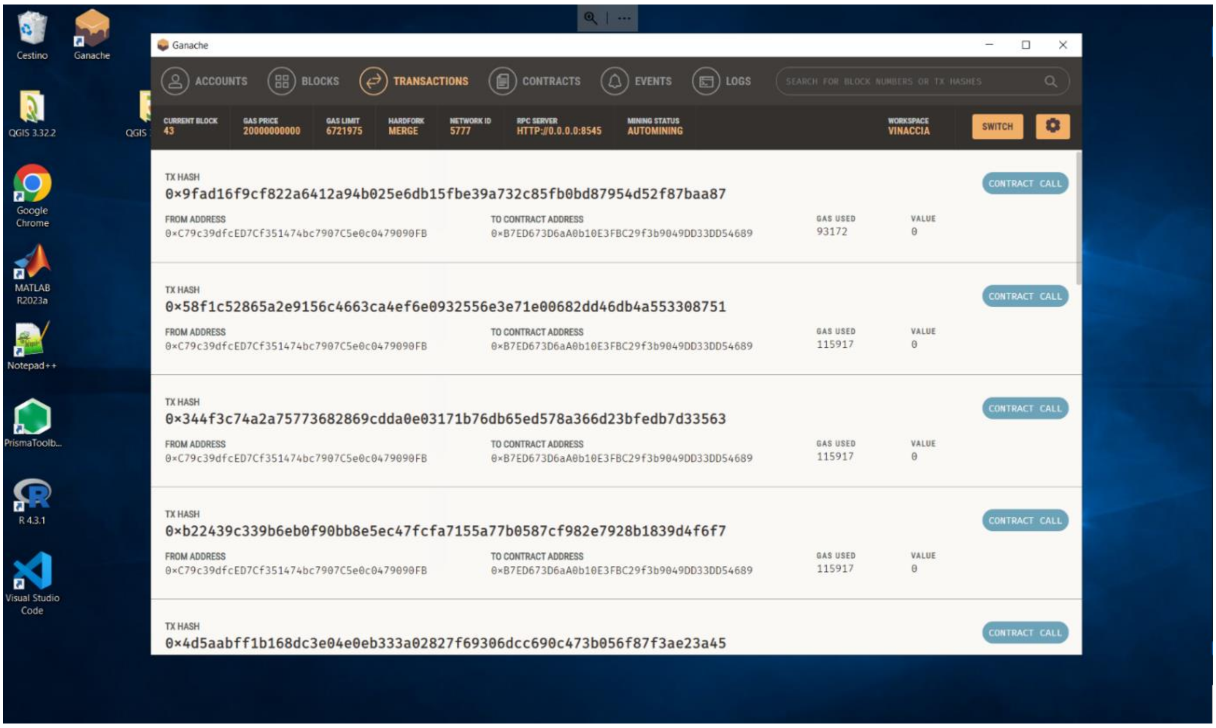


Figure 4.21 use of the timestamp to retrieve the hash of the batch from the blockchain.

Ultimately, is important to note that by recording information on a public blockchain, the system makes product data available to anyone possessing the batch identification code. This can be used to grant external actors, including consumers and governments, access to product information. Figure 4.22 illustrates how the proposed solution could improve product traceability within the wine supply chain. The figure distinguishes between four distinct levels. The first level highlights the stakeholders involved in the traceability of wines. These include grape growers, winemakers, certifiers, and consumers who retrieve product information. Each stakeholder plays a distinct role in ensuring transparency and reliability throughout the supply chain.

The second level details the physical operations carried out by each actor. Grape growers manage and harvest grapes, winemakers oversee the transformation of grapes into wine, and certifiers validate the compliance of processes and products with standards. Consumers interact with the system by accessing information about the wine's origin and quality.

The third level focuses on data management. It specifies the information that each stakeholder is required to record within the system to ensure complete traceability. This level connects physical operations to their digital representation.

The fourth and final level illustrates how storing the information on a public blockchain can improve traceability by ensuring accountability and reliability and fostering trust among the supply chain actors. Specifically, the figure shows how smart contracts can be integrated in the solution to automatically validate and append data on the blockchain, and to allow consumers to retrieve product information.

Finally, it is worth noting how the proposed solution enables direct interaction among different actors in the supply chain. This approach actively involves grape growers, winemakers, and certifiers in the traceability activities, providing consumers with comprehensive information about the product. Additionally, by minimising the number of transactions required to record data on the blockchain, the proposed solution aims to reduce costs and system complexity without compromising transparency and security, thereby addressing some of the most pressing companies' needs.

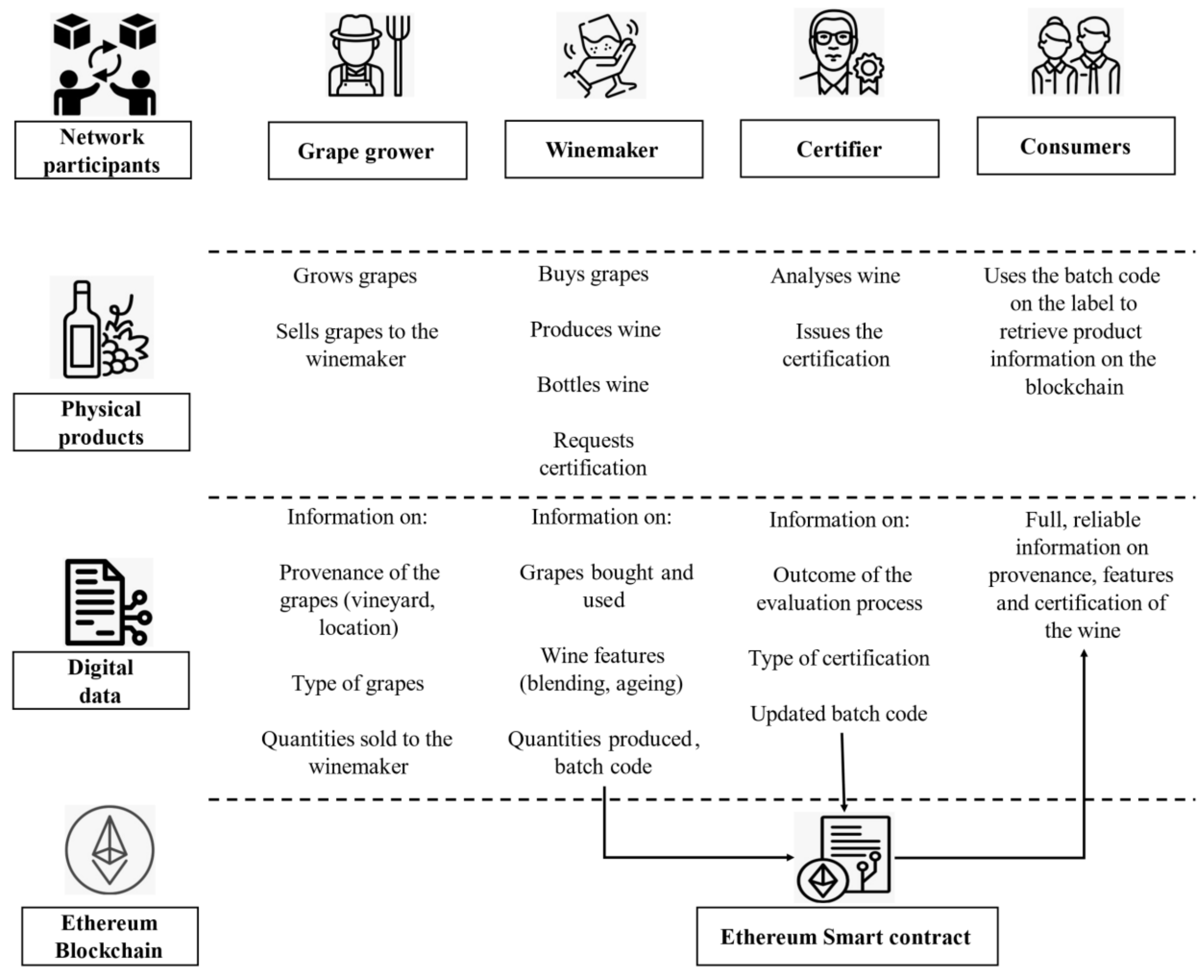


Figure 4.22 blockchain-enhanced traceability in the wine industry.

4.5 Discussion and conclusions

After presenting the architecture and the main features of the developed solution, and demonstrating its features through illustrative examples, this section concludes the chapter by reflecting on the results achieved. The strengths, weaknesses, and potential developments will be evaluated in contrast to the characteristics of the system currently employed by the Italian government, the SIAN, and referring to the requirements that a blockchain system must possess to meet the needs of Italian wineries, as identified and thoroughly analysed in chapter three. This approach allows for a rigorous assessment of the results obtained and enables the identification of theoretical and practical implications.

Starting by comparing the proposed solution to the SIAN, it is worth recalling that, while the SIAN currently serves as a relatively effective tool used by the Italian government to control agrifood supply chains, it also exhibits several weaknesses. These relate to its limited effectiveness in fostering supply chain digitalization and can be synthesized by two elements. First, product tracking features are primarily intended to elicit regulatory compliance, and the SIAN system does not provide companies with services enhancing the management of product flows or enabling the acquisition of market intelligence. Second, the system is not developed to facilitate interactions between businesses and consumers, which are becoming increasingly important due to the renewed attention consumers are paying to the characteristics, provenance, and quality of wines (Del Rey & Loose, 2023; Le et al., 2023).

Conversely, the proposed solution is designed to enable product tracking in the wine supply chain, balancing regulatory compliance with business needs. As for the former, the system requires companies to input key information about production processes, including grape variety, origin, quantities, and process yields. Beyond the examples provided in this chapter, it is thus possible to envision blockchain systems taking into account much finer details, such as the use of additives or the generation of by-products. This would allow a level of control comparable to that of SIAN. From a business perspective, however, the system is designed to facilitate interaction among multiple actors, namely grape growers, winemakers, and certifiers. Furthermore, by leveraging the features of a public blockchain, the system paves the way for the integration of smart identification tools, such as QR codes, to enable direct relationships between supply chain actors and consumers (Antonucci et al., 2019; Cordeiro & Olsen, 2021; Sunny et al., 2020). This overcomes one of the primary limitations of the SIAN and may help address one of the most pressing needs of companies in the wine sector.

Moving on, the SIAN exhibits other significant weaknesses related to data acquisition and management processes. The first is the system's low transparency and auditability, which allows only the government to access and verify the information uploaded by companies. In contrast, a public blockchain-based solution, such as the one proposed in this chapter, would allow anyone to access the system and trace the product's origin. This is particularly important to provide companies and consumers with a new solution to promote and assess wine quality (Danese et al., 2021; Dos Santos et al., 2021).

The second weakness pertains to the high degree of centralization in the SIAN, where the Italian government retains absolute authority. While effective for control purposes, this approach limits the system's potential to foster coordination and the autonomous development of the wine industry. From this perspective, blockchain-based solutions can help balance security and decentralization by leveraging shared consensus mechanisms and ensuring information reliability and auditability (Casino et al., 2019; Hussein et al., 2023; Kamilaris et al., 2019). Alternatively, it is possible to consider the development of consortium or private blockchain solutions, which may be useful to balance transparency and privacy concerns (Helliar et al., 2020; Toufaily et al., 2021).

Finally, the SIAN's last notable weakness relates precisely to the low reliability and persistence of the information. Data can be modified several times by companies following prescribed procedures without leaving a trace. While this increases flexibility, it reduces the accountability of the supply chain and hinders the use of digital tracking systems to build trust-based relationships between companies and external stakeholders, including consumers. In contrast, blockchain-based solutions seem to lean toward increasing transparency and persistence of information over flexibility (Sharma et al., 2023; Sunny et al., 2020). This could be detrimental to businesses, and it is unclear how these two needs can be balanced at present.

Regarding the advantages of the SIAN, it is reasonably easy to use and highly accessible. Additionally, as a traditional information system, the costs of managing and recording information are generally lower than those of a blockchain system, which could increase due to additional expenses related to verifying and publishing transaction data. However, this does not account for the costs associated with duplicating reporting activities that many companies face due to the necessity to update their information systems in addition to the SIAN. Finally, when considering the widespread use of blockchain-based systems, it's important to acknowledge persistent technological limitations such as scalability and throughput, which do not affect traditional information systems like SIAN. Table 4.1 shows how the main weaknesses of the SIAN system can be mitigated, by comparing the features of the digital information system adopted by the Italian government with the characteristics of the proposed blockchain-based solution.

Table 4.1 comparison between the main features of the SIAN and the characteristics of the blockchain-based solution described throughout the chapter.

SIAN system	Blockchain-based solution
Mainly focused on supply chain control	Ability to balance control and business needs
Does not allow interaction between supply chain actors	Enables interaction between supply chain actors
High degree of centralization	High flexibility in determining the degree of centralization
Low auditability	High auditability
Low reliability and persistency of information	High reliability and persistency of information
Simple to use and accessible	Simple to use and accessible
Low information recording and updating costs	High transaction verification costs
Performance on par with traditional information systems	Persistent technical limitations

Shifting to the analysis of how the proposed solution addresses the challenges and opportunities of blockchain adoption in the wine industry, several observations can be made. First, previous results highlighted that one of the major obstacles to the widespread adoption of blockchain in the Italian wine industry is wineries' lack of advanced technological skills (Cricelli et al., 2024; Malisic et al., 2023; Tiscini et al., 2020). This requires the development of simple-to-use solutions. The proposed system meets this requirement through design choices that make user interaction straightforward. Specifically, the user interface is designed to be intuitive and user-friendly, while more complex processes, such as the generation of blockchain transactions or data hashing, are executed autonomously in the background. This demonstrates that it is indeed possible to develop blockchain-based solutions tailored to industries characterised by low technological capabilities.

Moving forward, another key barrier was the difficulty for businesses in evaluating the costs and benefits associated with adopting a blockchain-based system (Kang et al., 2023; Saurabh & Dey, 2021). While a detailed cost analysis lies outside the scope of this discussion, the proposed system shows great flexibility. Considering its functionality and architecture, it is reasonable to assume that the deployment of a similar solution would be comparable with the adoption of a digital information system, with the notable exception of the additional costs related to the execution and verification of transactions. These steps, essential to record information on the blockchain and ensure security and transparency, require the payment of a fee. Thus, unlike traditional information systems, the cost of operating a blockchain-based system depends significantly on transaction fees and the number of transactions appended to the blockchain. This, in turn, is influenced by supply chain control requirements, as stricter controls necessitate more frequent updates (Menon & Jain, 2021; Wang et al., 2019). Consequently, transaction costs emerge as a critical parameter in the development of blockchain solutions.

Finally, another key consideration pertains to the ability to develop solutions that reconcile supply chain control with marketing opportunities (Cricelli et al., 2024). From this perspective, the proposed system illustrates how it is possible to design solutions that connect different actors throughout the supply chain while ensuring precise product tracking. By enabling reliable and transparent data sharing among stakeholders, the system opens up possibilities for businesses to leverage supply chain information not only to ensure compliance but also to enhance consumer trust and engagement.

Despite the insights gained by combining the findings of chapter three with the analysis of the features of the solution proposed in this chapter, several open issues remain. First, while the findings enable envisioning the costs entailed in developing a blockchain solution for product tracking in the wine industry, they do not allow a precise, quantitative analysis of costs and benefits. On the benefits side, it is crucial to evaluate whether blockchain enhances information flows, boosts sales, strengthens brand reputation, or reduces losses from counterfeiting. Regarding costs, key aspects include changes in product and data management expenses, transaction fees, and the scalability of blockchain systems across different business models. A thorough analysis of these factors would support businesses and policymakers in determining the feasibility and long-term sustainability of blockchain implementation in the agrifood sector. Indeed, this would only be possible following the diffusion of such solutions in the industry. This legitimizes the difficulty wineries face in conducting credible cost-benefit analyses. Furthermore, as suggested in chapter three, this issue is exacerbated by companies' limited awareness of blockchain technology (Adamashvili et al., 2021; Sander et al., 2018). This stresses the importance of fostering knowledge sharing through active policies promoting partnerships among businesses, technology providers, and research institutions.

Second, while the results indicate that it is feasible to design systems aligned with the current regulations, they also highlight how such elements may impact the development of effective solutions for real-world applications. From this perspective, the lack of shared regulations remains a significant obstacle that warrants attention from policymakers (Hughes et al., 2019; Kamilaris et al., 2019).

Finally, the results do not allow for an evaluation of the impact of known technological limitations on the development of blockchain solutions for large-scale applications. Although this technical perspective was not the central focus of the study, it is crucial to acknowledge that the development of blockchain solutions for large-scale applications is hindered by well-known constraints such as scalability, throughput, and latency, among others (Casino et al., 2019; Dutta et al., 2020; Zhao et al., 2019). From this perspective, the proposed solution seeks to address these limitations by reducing the number of transactions executed. However, future research could explore how to balance efficiency and performance based on the needs of the companies and the type of system, distinguishing between public, consortium, or private blockchains.

Overall, this chapter provides some relevant theoretical and practical implications. As for the former, this study offers two main contributions to the literature. First, by focusing on the case of the Italian wine industry, it illustrates how the unique industry characteristics, challenges, and opportunities may influence the development of blockchain-based solutions. This provides a nuanced understanding of how sector-specific dynamics may impact blockchain adoption in supply chain applications and highlights the importance of taking into account environmental, managerial and organizational aspects. Second, the study advances the understanding of the potential of blockchain solutions to reconcile control and business needs. By bridging these two dimensions, the research highlights the importance of designing systems that balance compliance requirements with the ability to foster collaboration, transparency, and efficiency across supply chain actors.

In terms of practical implications, the results of this study allow to provide some useful insights to practitioners, and policymakers. First, the findings suggest that it is possible to develop blockchain systems encompassing all actors in the wine supply chain, from grape growers to winemakers and certification entities. This highlights the pivotal role that consortia and institutions can play in engaging businesses and guiding technology providers toward the development of integrated solutions. The findings highlight the flexibility of blockchain-based systems in terms of costs and architecture. Practitioners should evaluate transaction volumes and information needs based on their goals, while businesses, associations, and institutions should collaborate to balance the trade-offs between public and permissioned blockchain platforms. Finally, the results suggest how is indeed feasible to provide external actors, including consumers, access to reliable product information using blockchain-based systems. This should prompt companies and technology providers to explore solutions to capitalize on this opportunity, fostering trust and enhancing value along the supply chain.

Despite its contributions, this chapter is not exempt from limitations. The first limitation lies in its focus on the Italian wine industry. While the choice to focus on a real-world case enabled a deeper understanding of how industry dynamics and environmental conditions can influence the development of blockchain-based solutions for practical applications, this limits the generalizability of the findings. Future research could address this shortcoming by contrasting these results in different contexts. Additionally, empirical studies could explore how environmental factors, or regulatory constraints impact the development of blockchain solutions. Alternatively, future research could investigate how these findings might vary when applied to different industries, and sectors.

The second limitation pertains to the study's inability to provide a reliable assessment of the benefits associated with the adoption of a blockchain-based tracking system in the wine industry. Future research could address this gap by analysing real-world cases and identifying metrics and indicators to assess the advantages that blockchain adoption might bring to companies in the wine industry. Such benefits could be evaluated from both an economic and a broader business perspective, encompassing factors such as brand reputation, consumer trust, and operational efficiencies.

A third limitation of the study is its lack of a detailed comparison of alternative technological solutions. Future research could address this gap by investigating ways to overcome known technical limitations of blockchain-based solutions for large-scale applications or by analysing how alternative solutions compare to the proposed blockchain-based system. For instance, it would be particularly valuable to explore the challenges and opportunities associated with adopting public blockchain solutions versus private blockchain systems, examining their respective implications for scalability, security, and interoperability.

GENERAL CONCLUSIONS

The thesis aimed to explore how technological innovation, specifically through Industry 4.0 technologies, can assist agrifood companies in balancing economic performance with sustainability objectives. This is particularly relevant given the pressing global challenges pushing agrifood companies to reconcile sustainable development, food security and accountability. Both governments and consumers increasingly require agrifood companies to mitigate environmental impacts, foster transparency, and remain economically sustainable. These needs are emphasized by the agrifood industry's unique role in addressing critical sustainability issues, such as resource scarcity, waste reduction, and food safety. Within this context, leveraging I4.0 technologies provides agrifood companies with the potential to redefine business models and innovate processes, addressing longstanding economic and sustainability challenges while meeting rising stakeholder expectations.

The first chapter of the thesis lays the foundations for understanding how I4.0 technologies may affect the sustainability of the agrifood industry through a comprehensive literature review aimed at addressing three fundamental research questions:

RQ1) What are the main applications of Industry 4.0 technologies in the agrifood industry, and how do technologies align with the characteristics of different agrifood supply chains?

RQ2) What is the state of research on technological innovation for sustainability in the agrifood industry?

Answering the first research question, the chapter proposes a taxonomy of I4.0 technologies in the agrifood industry, grouping them into four main clusters based on application domains, namely monitoring and control, resource management, product tracking, and information management. Next, the chapter provided an in-depth analysis of how I4.0 technologies can be leveraged by three core typologies of agrifood supply chains, depending on their unique dynamics and objectives. First, industrial supply chains offering perishable, non-differentiable products may particularly benefit from resource optimization technologies to enhance efficiency and minimize waste. Second, supply chains supplying higher-end, differentiable products could leverage tracking technologies, such as blockchain, to promote product identity and brand differentiation. Third, alternative food networks may attain significant advantages by using I4.0 to streamline operations and enhance the management of information and product flows.

Thus, the first chapter laid a robust theoretical foundation for understanding the role of I4.0 technologies in reconciling sustainability and economic goals in the agrifood industry. As for the second research question, the chapter highlighted the main findings and persistent gaps in the literature. This provided a starting point for subsequent investigations, leading to a focus on the impact of I4.0 technologies on the social sustainability of agrifood companies, and emphasizing the need to confront theoretical results with the analysis of particularly significant cases.

Consistently, the second chapter focuses on assessing the impact of I4.0 technologies on the sustainable development of the agrifood industry, with a particular focus on social sustainability. As highlighted in the previous chapter, the adoption of I4.0 technologies may enable a shift toward data-driven, more efficient and sustainable farming practices. However, while the environmental and economic benefits of I4.0 adoption are well-documented, the social sustainability dimension remained underexplored, especially from an empirical perspective. Chapter two aimed to bridge this gap by answering the following research question:

RQ3) How does the use of I4.0 technologies affect the social sustainability of agrifood companies?

To address this research question, several steps were required. Observing the lack of established theoretical frameworks, the first step involved developing a robust theoretical model to measure the impact of I4.0 technologies on key aspects of social sustainability relevant to agrifood companies. Ultimately, three key social sustainability dimensions are identified, respectively related to sustainable human resources management, sustainable supply chain management, and sustainable stakeholder management. As for the former, the literature suggests that the adoption of I4.0 technologies may improve working conditions by assisting activity planning and supporting agrifood workers by supporting the execution of the most repetitive and demanding tasks. In terms of supply chain management, the use of I4.0 technologies can strengthen relationships within the supply chain by improving traceability, transparency, and accountability. Finally, the adoption of modern tracking solutions can help agrifood companies build trust with consumers and external stakeholders, also ensuring compliance with sustainability standards and accountability.

Subsequently, to frame how I4.0 technologies affect business operations, the concept of technological capability was employed. This concept encompasses three critical dimensions, namely skills, strategic orientation, and technological maturity. Finally, the model was validated and tested using the SEM methodology, through an empirical investigation based on the expertise of 116 Italian agrifood companies. The chapter clearly highlights the complexity of the relationship between technological innovation and social sustainability, emphasizing the

pivotal role of skills development and the necessity for companies to achieve a certain level of technological maturity to fully unlock the potential benefits of I4.0 adoption.
Building on the outcomes of the first two chapters, chapter three takes a more focused approach, confronting theoretical implications with the case of blockchain adoption in the Italian wine industry. This is a particularly compelling case due to the great potential of blockchain technology in helping wineries combine social sustainability goals and economic performance. Indeed, due to the unique characteristics of high-end wines and the importance that provenance plays in the wine industry, adopting blockchain-based tracking solutions could help companies effectively market products and contrast counterfeiting phenomena. At the same time, product tracking is essential to achieve key social sustainability goals, ensuring safety, transparency, accountability, and compliance with regulations. Thus, the chapter complements the conceptual approach adopted in chapter two by investigating the impact of I4.0 technologies on the social and economic sustainability of agrifood companies in a real-world context. This allowed to focus on how industry dynamics, managerial challenges and opportunities may influence the technological innovation of companies in the agrifood industry, thus answer the following research question:
RQ4) What are the drivers and challenges of adopting blockchain-based systems for SMEs in the wine industry?
To answer this question, the chapter leverages a multiple case study analysis, drawing on 16 interviews with managers from Italian wineries. This allowed to provide a nuanced perspective on the intersection of technological innovation, industry dynamics, and sustainable development opportunities. The findings reveal a complex picture in which the benefits provided by blockchain, such as enhanced transparency, fraud prevention, and consumer trust are counterbalanced by significant barriers, including high implementation costs, a lack of technical expertise, and a lack of policies and regulations.
Results highlight the key role of managerial commitment in driving technological adoption. For many SMEs, blockchain adoption hinges on the willingness of top management to invest in innovation and prioritize digital transformation. However, even with strong managerial support, financial constraints often pose a significant obstacle. The high costs associated with blockchain systems, coupled with the difficulty of assessing potential benefits, make it difficult for SMEs to justify the investment. This is particularly true as wineries struggle to acquire technological capabilities and prefer to focus on marketing and communication.
Thus, the study highlights the importance of designing blockchain systems that align with wineries' needs and adapt to industry trends. Results show that SMEs require systems that are

user-friendly, cost-effective, and easily integrated into existing processes. Additionally, compliance with regulatory standards is a key consideration, as wineries operate in a heavily regulated environment where adherence to labelling, and traceability norms are crucial.

Beyond such benefits, the findings also suggest that blockchain technology has significant potential as a marketing tool. By providing consumers with verifiable information about the origin and production of their wine, blockchain can help wineries differentiate products in a highly competitive market. Indeed, the ability to reconcile supply chain control and marketing opportunities could be a decisive factor in eliciting the widespread adoption of blockchain in the Italian wine industry. Synthesizing, chapter three shows blockchain technology holds significant promise for transforming the wine industry, offering solutions to critical challenges such as traceability, fraud prevention, and consumer trust. However, its adoption among SMEs remains limited due to a combination of technological, organizational, financial, and regulatory constraints.

Chapter four flows naturally from these findings, investigating how blockchain tracking systems can be adapted to companies' needs, regulatory requirements, and market dynamics to reconcile economic and social sustainability objectives. This helps contrast conceptual analyses with pragmatic issues relating to managerial, organizational, and technological challenges that need to be overcome in order to seize the advantages promised by blockchain adoption in agrifood supply chains. Building on this foundation, the fourth chapter extends previous investigations by answering the following research question:

RQ5) What are the strengths, limitations, and requirements for the effective development of blockchain-based tracking systems in the wine industry?

To answer this question, the fourth chapter examines the development of a blockchain-based solution tailored to the needs of Italian wineries, offering insights into how these systems may be designed to effectively address economic and sustainability challenges affecting the wine industry. From this perspective, the chapter shows how the adoption of blockchain systems enables the tracking of products throughout the supply chain, connecting grape growers, winemakers, certifiers, and consumers while ensuring safety and compliance with current regulations. The chapter also shows how, by leveraging blockchain's ledger, it is possible to provide transparent and verifiable data about every step in the production process, including the origin of grapes, production methods, and quality control measures. This is not only useful to comply with regulations, but also to provide consumers with easy access to verifiable information about the product, helping wineries build trust and gain competitiveness.

Despite these advantages, results also show that the development and deployment of blockchain-based tracking systems entail significant challenges. Referring to chapter three, one of the main obstacles is the lack of advanced technological skills. Many small and medium-sized wineries do not possess the expertise required to implement digital solutions. To address this challenge, the proposed blockchain system was designed to be effective, yet simple to use, as complex processes are executed in the background.

Another significant challenge relates to the evaluation of costs and benefits associated with blockchain adoption. While the potential advantages of blockchain are well-documented, the costs of implementation and the transaction fees can be a barrier for businesses, especially when compared to traditional information systems. The solution proposed in chapter four seeks to address this concern by enhancing flexibility and reducing the number of transactions needed while maintaining a high level of transparency and security.

Overall, this thesis contributed to advancing the understanding of how technological innovation can support agrifood companies in balancing economic performance and sustainable development. Through its four studies, it moved from a holistic, high-level perspective to a detailed analysis of the dynamics, challenges, and opportunities associated with real-world applications. In doing so, the thesis addressed key gaps in the existing literature and provided some relevant theoretical and practical contributions, which will be synthesized in the next sections.

Implications for scholars

This thesis advances the literature by providing three main theoretical contributions. First, the thesis introduced a managerial and organizational perspective to the investigation of innovative technology adoption in the agrifood industry. Most of the literature relies on conceptual approaches and overlooks crucial environmental and contextual factors or adopts a technology-centric perspective that emphasizes technical challenges and advantages. By adopting a more pragmatic perspective, the thesis analysed potential benefits against organizational, managerial, technological, and environmental challenges. Moreover, unlike many prior studies that emphasize the advantages of adopting innovative technologies, this thesis provides a nuanced evaluation that contrasts these benefits with the complexities influencing adoption in the agrifood sector.

From this perspective, the first chapter contributes by offering a classification of I4.0 technology applications based on application domains. This allowed for the identification of the main benefits that I4.0 technologies can bring to the agrifood industry. It also served as a foundation to explore how these technologies may impact three core types of agrifood supply chains, depending on their configuration, objectives, and specific needs. This analysis added a significant contribution to the literature by complementing technology-centric investigations with crucial managerial considerations. It also paved the way for subsequent studies by highlighting key under-explored areas.

This led to a focus on analysing the impact of technological innovation on the social sustainability of agrifood companies. This is critical, as previous studies mainly focused on the connections between technological innovation, economic benefits, and environmental sustainability. In this context, the thesis makes a significant contribution by developing and validating a robust theoretical framework for analysing the impact of Industry 4.0 technologies on three core aspects of social sustainability in agrifood companies. This enriches the literature by identifying reliable metrics and a robust model to support future investigations. Additionally, this also helps address a significant gap in the literature by providing much-needed empirical evidence on the effects of technological innovation on the social sustainability of agrifood companies. By referring to the concept of technological capability, encompassing skills, strategy, and maturity, and considering the implications in terms of social sustainability, the study offers a structured and reliable approach to assess the social implications of I4.0 adoption. As such, the theoretical model advanced in this chapter serves as a valuable tool for researchers and offers a deeper understanding of how agrifood companies can manage the complexities of technological innovation while addressing crucial social issues.

Lastly, the thesis makes a meaningful contribution by supporting conceptual analyses with empirical evidence. This grounded approach was instrumental in bridging the gap between theory and practice. On one hand, by integrating qualitative and quantitative studies, this thesis provides a stronger foundation for empirical research in the field. On the other, by focusing on the adoption of blockchain technology in the wine industry, it initiates the empirical investigation of this emerging phenomenon, illustrating how technological innovation may help agrifood companies reconcile social and economic sustainability. This helped analyse how industry dynamics, environmental factors, and organizational challenges may influence the adoption of innovative technological solutions in the agrifood industry. Thus, the thesis contributed to the literature on blockchain adoption by highlighting the importance of context-related factors for the effective deployment of technological innovations in agrifood applications.

Implications for practitioners and policymakers

Besides its theoretical contributions, this thesis also offers valuable practical insights to assist practitioners and policymakers in leveraging technological innovation to align business opportunities with sustainable development in the agrifood industry. The main practical contributions of the thesis are three.

The first stems from the findings of the first chapter, which can help companies evaluate how different technological solutions can enhance the sustainability of agrifood supply chains depending on their configuration, and dynamics. This emphasizes the importance of aligning technological adoption with supply chain characteristics. By understanding the interplay between technologies and supply chain features, managers can make informed decisions about investments in innovation. Furthermore, the study highlighted the importance of considering synergies between different technologies to achieve substantial advantages. Lastly, the findings suggest the key role played by coordination and information-sharing mechanisms within the supply chain to propagate the benefits of technological adoption within and outside the supply chain. For policymakers, the study suggests the importance of enacting regulations that facilitate the integration of multiple technologies. From this perspective, the definition of shared standards and targets concerning product traceability, communication protocols, and sustainability objectives may play a crucial role.

Moving on, the second chapter provides evidence of how technological innovation can support agrifood companies in achieving crucial social sustainability objectives. At the same time, the findings caution against underestimating the complexities and challenges involved in adopting technologies for social sustainability purposes. In terms of practical suggestions, the findings show how the development of technological skills is crucial to achieving social benefits, even beyond the boundaries of the firm. Indeed, the adoption of I4.0 technologies can improve supply chain management, fostering more transparent and responsible interactions with supply chain partners, and enhancing relationships with external stakeholders, including consumers and regulatory entities.

However, the study also highlights the importance of aligning the company's technological strategy with its social sustainability goals. By focusing solely on technological innovation and failing to consider the needs and interests of external stakeholders, companies may fail to achieve social benefits. In this, the findings point to the complexity of balancing the technological strategy with the management of stakeholder relationships. While an effective strategy is essential to seize the benefits of technological innovation, it may also divert attention and resources away from stakeholders' needs, leading to unsatisfying outcomes. The results of the study also underscore the importance of technological maturity in enhancing human resources management. Companies with higher levels of technological maturity are better positioned to integrate I4.0 technologies in ways that benefit and support the employees in the execution of their activities.

For policymakers, the findings suggest a critical role in guiding companies toward achieving social sustainability objectives. From this perspective, defining targets and establishing procedures to assess the social impact of agrifood companies becomes essential. Policymakers could leverage the transparency and information capabilities provided by I4.0 technologies to evaluate compliance with social sustainability standards and to ensure companies adhere to rules and guidelines. This would not only enhance accountability but also incentivize businesses to adopt strategies aligning technological innovation with broader societal goals.

Finally, the third contribution is linked to the results of the last two chapters, which analyse in detail the adoption of blockchain technology in the Italian wine industry. These chapters provide an in-depth examination of the challenges, opportunities, and requirements associated with blockchain adoption, considering the unique dynamics and environment characterising the industry. By doing so, the thesis offers wineries and policymakers actionable insights on how to leverage blockchain-based tracking systems to ensure safety, transparency, and accountability while gaining competitive advantages. Additionally, it provides technology providers with suggestions on how to develop blockchain solutions tailored to the needs of companies in the wine industry.

The findings suggest that blockchain has the potential to transform wine supply chains by strengthening the connections between all the actors and improving transparency and accountability. This may help companies reconcile social and economic sustainability goals, enhancing coordination and information sharing throughout the supply chain, and effectively contrasting frauds. Additionally, the results suggest that blockchain systems may provide significant benefits to companies and consumers alike. On the one hand, enhanced transparency enables consumers to make sound purchasing decisions. On the other, this may help the firms build trust relationships with customers and gain a competitive advantage. Lastly, blockchain-based solutions may replace traditional information systems, helping governments and policymakers oversee companies' activities and contrast fraudulent practices.

At the same time, results show that challenges related to scalability, cost, and technical expertise must be addressed to ensure the widespread adoption and long-term success of blockchain-based tracking systems in the wine industry. From this perspective, conducting cost-benefit analyses can help wineries assess the potential impact of blockchain adoption on combating counterfeiting and increasing sales and margins. For technology providers, the study highlights the need to develop blockchain solutions tailored to SMEs' needs, emphasizing ease of use, interoperability, and cost-effectiveness. Finally, policymakers also have a crucial role to play in supporting blockchain adoption through financial incentives, and training programmes. Furthermore, policymakers are encouraged to set up the conditions to foster partnerships between technology providers, universities, and research institutions to bridge knowledge gaps and develop industry-specific solutions. Policymakers may also contribute to blockchain adoption by agreeing on regulations and communication standards that may help newer solutions gradually replace traditional information systems.

Limitations and future research

Despite its contributions, this thesis is not exempt from limitations. Reflecting on these provides the opportunity to outline future research trajectories to address such shortcomings. Regarding the first chapter, a key limitation relates to the use of a literature review methodology, which may have inadvertently led to the exclusion of relevant contributions or introduced elements of subjectivity in the selection of articles. From this perspective, the exclusion of the keyword "digitalization" and similar terms from the search string is noteworthy. Indeed, while enabling a more focused analysis of Industry 4.0 technology applications in the agrifood industry, this choice inevitably constrained the size of the sample. Though deliberate, this may have led to the omission of relevant contributions exploring the intersection between digital transformation and sustainability in the agrifood industry. Future research could overcome this limitation by exploiting IA solutions to conduct a comprehensive, systematic literature review. This could enable the analysis of a vast number of studies, facilitating the identification of thematic connections and tracing the evolution of research over time. This may help mitigate selection biases and help scholars provide a data-driven understanding of the field's development.

Another limitation of the first chapter lies in its primary focus on the adoption of innovative technologies in the cultivation and production stages of agrifood supply chains. While this was necessary to narrow down the scope of the thesis, it resulted in a lack of attention to other critical sectors, such as farming and fisheries. Future research is required to gain a more holistic understanding of the role of technology in agrifood systems. Lastly, the first chapter did not explore in depth the use of technologies in the processing and distribution stages. Future investigations could focus on these stages to provide a better understanding of the end-to-end implications of technological adoption in the agrifood industry.

Moving on to the second chapter, a limitation pertains to the potential exclusion of relevant variables or the identification of more suitable metrics. This entails the possibility to define more comprehensive and precise models. Thus, future research could incorporate a broader range of socioeconomic variables, investigating the impact of variables such as firm size, environmental context, or regulatory pressure on companies' decisions to pursue social sustainability objectives through technological innovation. Examining these factors could provide valuable insights into the conditions that facilitate or hinder the integration of Industry 4.0 technologies in support of social sustainability goals. Also, future studies could focus on one of the three dimensions of social sustainability, enabling detailed analyses of specific issues. For instance, research could investigate how technological advancements contribute to the empowerment of agricultural workers, improving their working conditions and access to resources. Alternatively, future studies could explore the impact of digital technologies on relationships among actors within agrifood supply chains, shedding light on collaboration dynamics and power distribution across different stakeholders.

Another significant limitation of the second chapter concerns its empirical focus on the Italian context. While this choice provided valuable insights in relation to a highly industrialized and representative scenario, it limits the generalizability of the findings. Future studies should extend the analysis to diverse socioeconomic and political contexts to uncover regional differences and identify context-specific variables that may influence the adoption and impact of innovative technologies on the social sustainability of agrifood companies.

As for the third chapter, a limitation relates to the choice of adopting the case study methodology, which inherently entails elements of subjectivity in the selection and analysis of cases. Although the study presented in chapter three attempts to provide a neutral assessment of the opportunities and challenges associated with blockchain adoption by comparing multiple cases, future research could focus on large-scale quantitative investigations. This would allow a more generalizable understanding of blockchain implementation across different contexts, reducing the biases inherent in case study research and offering statistically robust insights. From this perspective, the drivers, challenges, and requirements of blockchain adoption identified in the third chapter could serve as a starting point for defining key determinants of blockchain adoption. Thus, future studies could develop technology diffusion and acceptance models that capture the interplay of technological, organizational, and environmental factors influencing blockchain integration. These models could help identify critical enablers and barriers to its widespread implementation across different sectors.

Additionally, a limitation shared by both the third and fourth chapters is the focus on a specific setting, namely the Italian wine industry. While this allowed to take into account unique industry dynamics, it also limited the generalizability of the results. Future research could explore the application of blockchain across a broader range of agrifood sectors, assessing how environmental factors shape adoption dynamics, challenges and opportunities. In fact, while sharing several similarities with other agrifood sectors, the wine industry also presents significant peculiarities. Indeed, wines exhibit greater variability in quality and characteristics, leading to a wide price range and a highly segmented market. Moreover, the Italian wine sector is characterized by a strong presence of small producers. These rely on their deep connection to the territory and the informed preferences of a niche of consumers to offer high-end, unique wines, thereby competing with larger wineries and more renown wine brands. Thus, wines are highly differentiable, making traceability particularly important. In this scenario, blockchain technology can serve to counteract fraudulent practices and support diverse business models, from artisanal winemakers emphasizing exclusivity and terroir to large-scale producers aiming to reinforce consumer trust through transparent supply chains. However, it remains to be determined whether these benefits are equally significant for other agrifood supply chains.

Indeed, a limitation of this study lies also in its focus on SMEs, which may limit the applicability of the findings to other industries dominated by larger companies or where blockchain needs to be integrated into complex global value chains. The challenges and opportunities of blockchain adoption can vary significantly depending on company size, as large corporations typically have greater financial and technological resources but also face higher regulatory complexity. Future research should explore these dynamics further to provide a more comprehensive understanding of blockchain adoption across different sectors, especially where authenticity and quality certification are crucial. A starting point could be the supply chain of organic products or other certified goods, where verifying provenance and production methods may play a key role in enhancing consumer trust and market value.

Another significant limitation of the studies presented in chapters three and four lies in the inability to quantify the benefits and costs associated with blockchain implementation. Regarding the benefits, it would be essential to evaluate not only how blockchain influences information flows throughout the supply chain but also its impact on the market. In this regard, future research could explore whether blockchain adoption leads to increased sales, enhances brand reputation, or mitigates the financial damage caused by counterfeiting and fraud.

As for costs, a critical area of investigation would be how blockchain adoption affects information and product management costs. Additionally, it would be necessary to evaluate transaction costs, and the expenses associated with scaling blockchain systems to accommodate different business models and supply chain structures. This analysis could help businesses and policymakers make informed decisions about the feasibility and sustainability of blockchain implementation in the agrifood sector.

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APPENDIX

Table A.1 provides a summary of the scales used to measure the latent constructs of technological capability and social sustainability in chapter 2. The table also presents items used to measure each indicator, along with a brief description.

Table A.1 latent variables, factors, and items.

Construct	Factor	Items
Industry 4.0 technological skills	TSK_1	The employees of the company possess advanced Industry 4.0 technological skills.
	TSK_2	The company invests heavily in the development of employees' Industry 4.0 technological skills.
	TSK_3	The company hires employees with advanced Industry 4.0 technological skills.
Industry 4.0 technological strategy	TST_1	The company can establish new technological standards.
	TST_2	The company is one of the leaders in the agrifood industry in terms of technological innovation.
	TST_3	The company can leverage the technologies to solve problems.
Industry 4.0 technological maturity	TMT_1	The company can integrate many Industry 4.0 technologies in business processes
	TMT_2	The company regularly uses Industry 4.0 technologies in business processes.
Sustainable supply chain management	SSC_1	Industry 4.0 technologies help the company establish trust relationships with partners.
	SSC_2	Industry 4.0 technologies help the company inform the partners about the CSR requirements to comply with.
	SSC_3	Industry 4.0 technologies help the company define and implement formal procedures to assess partners' CSR performance.
Sustainable stakeholder management	SSM_1	Industry 4.0 technologies help the company involve and consider the interests of the stakeholders in business decisions.
	SSM_2	Industry 4.0 technologies help company consider and address consumers' needs in business decisions.
	SSM_3	Industry 4.0 technologies enable the company to promote economic development in the communities where it operates.
Sustainable human resources management	SHR_1	Industry 4.0 technologies help the company ensure work-life balance for its employees.
	SHR_2	Industry 4.0 technologies help the company improve workplace healthiness through the dissemination of shared codes of conduct.
	SHR_3	Industry 4.0 technologies help the management to address workers' needs.

Table A.2 provides some essential information about the firms that decided to participate in the study presented in Chapter 3, including the base of operations, the role of the interviewee within the firm, the date of the interview, and the name of the firm if permission was granted.

Table A.2 essential information about the companies and the informants.

Company name	Headquarters	Number of employees*	Role of the respondent	Interview date
Tralci Hirpini	Southern Italy	12	Owner	05 – 31 - 2023
Joaquin Wines	Southern Italy	7	Sales manager	05 – 26 - 2023
Sella delle Spine	Southern Italy	Not available	Sales manager	06 – 05 - 2023
Vini Malavasi	Northern Italy	6	Owner	07 - 13 - 2023
Francesco Maggi	Northern Italy	10	Owner	07 – 28 - 2023
Company A	Southern Italy	10	Owner	07 – 10 - 2023
Company B	Southern Italy	15	Owner	06 – 01 - 2023
Company C	Southern Italy	8	Owner	06 – 15 - 2023
Company D	Southern Italy	21	Production manager	06 – 20 - 2023
Company E	Southern Italy	7	Production manager	06 – 21 - 2023
Company F	Northern Italy	20	Owner	07 – 06 - 2023
Company G	Northern Italy	13	Owner	07 – 28 - 2023
Company H	Northern Italy	Not available	Production manager	07 – 12 - 2023
Company I	Central Italy	4	Owner	07 – 10 - 2023
Company L	Central Italy	6	Owner	06 – 08 - 2023
Company M	Central Italy	15	Production manager	07 – 04 - 2023

*Number of employees relates to the number of people employed on a permanent basis. As such, seasonal workers are not included in the count.