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RETHINKING THE AGRI-FOOD SUPPLY CHAIN IN LIGHT OF THE DIGITAL AND SUSTAINABLE TRANSITION

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1. Introduction

The agri-food industry has received increasing attention in recent years. Due to significant carbon emissions, environmental damage, and depletion of natural resources, many experts believe the existing food and agricultural system is unsustainable (Campbell et al., 2017). Indeed, increased agricultural productivity, driven chiefly by mechanisation and heavy fertilisers and pesticide use, generates significant pollution, releasing toxic substances into the airborne, waterways, and land (Tasca et al., 2017). In addition, even households' daily diets have environmental implications. For example, diets high in meat and dairy products are generally not beneficial to the environment since animal protein consumption has been a determinant of climate change, with roughly 7.1 gigatons of equivalent carbon dioxide (CO_2-eq) emissions (FAO, 2020). The Sustainable Development Goals (SDGs) of the United Nations' Agenda 2030 aim to eradicate malnutrition and hunger and guarantee sustainable consumption and manufacturing systems by 2030 (Duro et al., 2020). However, the world population is estimated to grow to 8 billion inhabitants by 2024 and 9.5 billion by 2050 (Sehnem et al., 2020), and simply expanding food production is not enough to achieve the SDGs. The fundamental goal of food sustainability is to ensure sufficient food for the world's population, not to deplete the planet's resources, and in that view, not to prevent future generations from meeting their food needs (El Bilali, 2019). Global food security is a critical concern for humanity (Lombardi et al., 2019), and a more urgent system for global sustainability is needed, minimising natural resource extraction and consumption and reducing the amount of food loss and waste (FLW) (Dora et al., 2021). Indeed, while the focus is on increasing agricultural production by 50–70% to meet this goal, one frequently overlooked issue is FLW mitigation (Abdelradi, 2018). The agri-food sector is responsible for a large amount of waste generated. Recent data published by the FAO have shown that approximately 33% of all foodstuffs manufactured worldwide, corresponding to approximately 930 million tons, is lost or wasted somewhere along the food supply chain (FSC) (Abbate et al., 2023c; Dora et al., 2021); this amount has a $750 billion production value (Slorach et al., 2019). Specifically, food loss arises during the production phase due to unfavourable weather conditions, damaging practices, and an absence of adequate facilities. In contrast, food waste arises when households consciously discard nourishing foodstuff after failing to schedule their meals appropriately (Rasool et al., 2021). In addition to a significant economic cost, FLW are profoundly unethical given that about one billion people worldwide currently suffer from food scarcity (Ciulli et al., 2020). Further, the disposal and landfilling of food waste as well as the implied overproduction and overexploitation of natural resources have substantial negative environmental implications (Devin and Richards, 2018). As a result, FLW pose major environmental, economic, and social problems that the whole value chain must address immediately (Cicculllo et al., 2021). Among the primary issues in the current agri-food supply chain leading to FLW are a lack of industrialisation, inadequate management practices, and inaccurate information (Kamble et al., 2020). Indeed, while food systems are increasingly mechanised to improve economic performance (namely productivity), this automation should be aimed at preventing and reducing FLW.

The scientific literature shows that the household level is the value chain stage where food is discarded most frequently (Gaiani et al., 2018). This is particularly true for industrialised countries. Indeed, according to Stancu et al. (2016), in higher-income nations (e.g. Europe), the household level is the most significant contributor to FLW. In contrast, in countries with lower incomes (e.g. Sub-Saharan Africa), agricultural and post-harvest stages produce the majority of the FLW. Households' food waste is a major challenge for sustainable development as it directly affects the consumer economy, causes loss of natural resources, and generates greenhouse gas emissions. Indeed, when edible food is thrown away, all resources used in its production, processing, and transportation are wasted (Soorani and Ahmadvand, 2019). Notably, FLW are responsible annually for dispersing 253 billion cubic meters of drinking water and generating about 1.5 gigatons of CO_2-eq emissions, corresponding to approximately 6% of the year's world greenhouse gas (GHG) emissions (FAO, 2020). In addition, 1.4 million hectares of arable land, corresponding to 28% of the earth's surface for agriculture, are used to produce food that will never be eaten, contributing significantly to biodiversity loss, both animal species and vegetables (FAO, 2020). As a result, FLW prevention and reduction could be a solution for increasing the amount of food available worldwide and feeding the world's expanding population (Stancu et al., 2016), reducing the environmental implications of the value chain, and avoiding economic losses (von Kameke and Fischer, 2018). It offers the greatest economic, social, and environmental advantages when compared to other waste-handling techniques (Soorani and Ahmadvand, 2019).

Due to its environmental sustainability challenges and the vast quantity of waste produced, agriculture has been recognised as one of the primary areas where the circular economy (CE) paradigm may be implemented (Fassio and Tecco, 2019), allowing for FLW valorisation during all the stages of the agri-food supply chain (Principato et al., 2019). A large quantity of food produced goes waste and moving to a circular supply system is necessary to preserve the environment, climate change, and biodiversity (Kirchherr et al., 2017a). Indeed, the CE principle repurposes FLW as new resources for manufacturing inputs or raw materials for other uses, such as livestock feed (Principato et al., 2019). The transition towards the CE in the agri-food supply chain will need the right support mechanisms (Santagata et al., 2021); the top three barriers to adopting CE principles in the agri-food supply chain are institutional, financial, and technological challenges (Mehmood et al., 2021). Institutional challenges refer to the absence of performance standards evaluation, inadequate cooperation between new laws and current rules, ineffective recycling procedures to obtain products of high quality, and unclear tax laws relating to recycled goods. Financial barriers refer to high economic costs related to CE implementation in the agri-food sector. Finally, technological challenges include uncertainty regarding the product's end-of-life phase and difficulties in sustaining a product's quality and durability throughout its lifecycle. However, the CE is intended to contribute to the current ecological transition, providing economic advantages, reducing environmental damage, and preserving global society for future generations (Mancuso, 2021). For this reason, the CE is recognised as a transitional path toward reconciling environmental and socioeconomic dimensions (Lazarevic and Brandau, 2020). Different definitions of CE are used in the scientific literature, and it is most frequently described as a mix of reusing, recycling, and reducing strategies (Kirchherr et al., 2017b). Thus, the CE model promotes more sustainable and responsible resource exploitation, repurposing resource-rich by-products instead of the linear "take-make-dispose" approach (Santagata et al., 2021).

Furthermore, although the idea of short supply chains is not to reduce waste, the scientific literature highlights that, due to their unique properties and small scale, short food supply chains (SFSCs) could contribute to sustainability, facilitating the adoption of CE practices (Fogarassy et al., 2020; Forssell and Lankoski, 2015). Indeed, according to Kiss et al. (2019), this kind of chain can help prevent food waste and support the goals of CE: reducing the number of steps from producer to the consumer can guarantee a lower rate of the perishability of products and, therefore, less waste of resources and less FLW. These losses may occur, for instance, when wholesalers or retailers compel producers to overproduce or reject goods that do not satisfy their standards (Kiss et al., 2019; Priefer et al., 2016). Further, purchasing local goods is strongly linked to sustainability and developing an economically and socially sustainable society. Indeed, adopting a short supply chain system means promoting and straightening local economies, discovering the traditions and the link with the territory, while also reducing the need for lengthy and polluting transports and the use of chemicals strictly necessary during industrial processing, reducing the overall environmental impact (Kiss et al., 2019). Therefore, SFSCs can help improve the three dimensions of sustainability and create a circular ecosystem (Kiss et al., 2019; Czikkely et al., 2018).

Furthermore, the European Union (EU) is one of the most active participants in the CE transition. For example, in 2021, the EU launched the new CE Action Plan with the aim, among others, of making all kinds of packaging put on the EU marketplace reusable or recyclable by 2030 (European Commission, 2021a). These policy measures establish a consolidated plan of action with initiatives and legislative proposals to aid the transition to the CE and sustainable development Ghisellini and Ulgiati, 2020). Although the EU recycling and recovery rates have progressively improved, the amount of packaging trash created per European resident has grown from 163.3 kg in 2007 to 169.7

kg in 2017 (Sazdovski et al., 2021). However, thanks to reduction, reuse, recycling, and redesign strategies, the CE can reduce the environmental implications linked to food packaging, which is considered a great source of concern due to its enormous production volume, short use period, and waste management issues (Geueke et al., 2018). According to Masmoudi et al. (2016), biodegradable and recyclable packaging, such as made of polylactic acid (PLA), can help prevent severe disposal issues. Further, in SFSCs, producers employ less or zero packaging. This is because of how they conduct their business and sales activities: compared to large chain stores, fewer products are sold and fewer restrictions on how customers can shop (Kiss et al., 2019). In addition, appropriate packaging choices can directly or indirectly reduce the FLW across the supply chain. In the EU, the final consumption phases of the supply chain (households, food services, and retailers), the most sensitive to packaging with effective food preservation capabilities, contribute to 70% of food waste generation (Nicastro and Carillo, 2021). As a result, relevant parties such as food producers, manufacturers, brand owners, retailers, and consumers, as well as packaging legislation regulators, should be aware of the relationship between packaging design and FLW: properly designed packaging can ensure better preservation of food, prolonging its shelf-life, thus resulting in less FLW (Wikström et al., 2014). In addition, food packaging and labelling is a crucial aspect guiding consumers towards more sustainable and circular choices. According to Aitken et al. (2020), the foundation for consumer choice is a clear, honest, transparent food labelling. Thanks to appropriate labels on the product packaging, consumers attempt to distinguish sustainable and circular food goods from conventional ones (Sangkumchaliang and Huang, 2012). With these premises, the CE aims to: (1) improve waste management methods via pro-active design, reuse, and recycling; (2) reduce fossil resources consumption and increase the use of renewable energy sources; (3) reduce non-essential goods' production; and (4) implement "circular" governance with enhanced collaborative strategies (Santagata et al., 2021).

In addition to embracing the CE paradigm, FLW prevention and reduction could be achieved by implementing and exploiting the new enabling Industry 4.0 (I4.0) technologies. The term "Industrie 4.0" denotes the fourth industrial revolution, or I4.0 (Li 2018), and it was first used at the 2011 Hannover Expo by Henning Kagermann, a physics professor involved in changing the German industry development strategy (Gajdzik et al., 2020). According to Schmidt et al. (2015), I4.0 is described as “the embedding of smart products into digital and physical processes”. Indeed, the I4.0 concept is strictly related to the adoption and exploitation of new digital technologies, such as the Internet of Things (IoT), cloud computing, and big data analytics (Leone et al., 2021), whose application leads to an improvement in the overall corporate performance (Warner and Wäger, 2019). In addition, I4.0 includes advanced manufacturing solutions (e.g., integrated sensors and cooperating industrial robots), flexible automation, simulation technologies, additive manufacturing/3D printing (Xu et al., 2018; Ejsmont et al., 2020), radio-frequency identification (RFID) systems, blockchain (Bonilla et al., 2018), augmented/virtual reality, horizontal/vertical integration, and cybersecurity (Culot et al., 2020). At the heart of I4.0 are the concept of cyber-physical system (CPS) to monitor physical processes, make smart decisions, and provide real-time communications (Zhong et al., 2017). Therefore, I4.0 is characterised by advanced production methods which are wholly or partly automated, where different machines autonomously communicate with each other along the production line (Akyazi et al., 2020). Therefore, I4.0 has been hailed as a suitable route for raising productivity, fostering business growth, and guaranteeing the long-term sustainability of manufacturing companies (Rosin et al., 2020). Regarding the economic perspective of I4.0, transparency and interconnection of operations are the main characteristics leading to process optimisation, boosting efficiency, flexibility, quality, and customisation (Hossain et al., 2016; Müller et al., 2018). Regarding the environmental dimension, I4.0T may significantly support companies in reducing pollution, GHG emissions, and energy and resource consumption, thanks to greater efficiency of operations along with the supply chain (Azevedo et al., 2012; Schoenherr and Talluri, 2012; Ejsmont et al., 2020). Today, natural disasters, such as floods and hurricanes, are even more frequent, and it is partly due to climate change; businesses should reorganise their supply chains to enhance profitability and competitiveness while reducing the environmental implications of their operations (Dolgui et al., 2020). Regarding the relationship between I4.0 and corporate social responsibility, it is essential to point out that I4.0 includes several advantages for employees. Using intelligent assistance technologies and innovative human-machine interfaces, I4.0 implies considerable training and learning activities that boost employees' job satisfaction (Herrmann et al., 2014; Müller et al., 2018).

The fourth industrial revolution has been transforming many companies' business models, including those of the food industry. There is a widespread belief that the new Industry 4.0 (I4.0) enabling technologies have the capacity to revolutionise agriculture completely (Shepherd et al., 2020). According to recent studies (e.g. Ojo et al., 2018), food production must double by 2050 to satisfy the estimated demand from the world's growing population, and the I4.0T can support companies in increasing food production with fewer resources, reducing FLW and the overall environmental implications (Lezoche et al., 2020; Galanakis et al., 2021). In agriculture, many of the expected advantages of digitalisation focus on higher efficiency via precision mechanisation, automation, and better decision-making (Fielke et al., 2020), as well as higher traceability through the collection and sharing of data in real time (Saetta and Caldarelli, 2020). Customers are increasingly looking for information on the whole supply chain of agri-food goods after several food safety risk occurrences and scandals in recent decades, such as the mad cow disease and horsemeat scandals (Zhao et al., 2019). Consequently, various key I4.0 technologies, such as the IoT and blockchain, have the potential to improve food safety - which has become a top priority internationally - by enabling product identification, tracking, and tracing throughout the supply chain stages (Akyazi et al., 2020; Mangla et al., 2022). According to Annosi et al. (2021), the food supply system in Europe wastes 88 million tons of food produced and destined for human consumption every year. Therefore, traceability in the agri-food industry plays a significant role in increasing food quality and safety (Kayikci et al., 2020), reducing the number of incorrect deliveries, excessive waiting times, and product losses (Müller et al., 2018), therefore optimising the entire agri-food supply chain. Moreover, developing wireless sensor technology (WST) applications in precision agriculture enables greater performance, productivity, and profitability while mitigating unintended environmental and wildlife damage (Ruiz-Garcia et al., 2009). For instance, humidity and temperature sensors provide real-time knowledge from the fields (Adenugba et al., 2019), offering farmers a good foundation for adjusting strategies accordingly. As a result, there is evidence that innovation is critical to long-term sustainability in terms of technological improvements, optimisation, and efficiency of production systems (Aschemann-Witzel and Stangherlin, 2021). The adoption and integration of the new digital technologies (e.g. blockchain, IoT, big data) thus contribute to faster industrial transformation in the agri-food industry, transform business model companies within the sector and encourage the development in a shorter period and at a reduced cost of high-quality goods (Akyazi et al., 2020). For modern enterprises aiming to survive and gain competitive advantages in a digital economy, this new technological paradigm has become increasingly important (Liu et al., 2011). Using I4.0 technologies, primary agricultural goals such as water saving, soil conservation, carbon mitigation, and improved production can be achieved (Lezoche et al., 2020). As for rice farming – which is the third-highest produced crop worldwide – recent literature have shown that modern technologies could increase the rice yields and reduce rise production costs (Hou et al., 2020). Thanks to these new tools, it is possible to face various sustainability challenges, such as waste disposal and growth in food production (Appio et al., 2019), with a significant influence on society (Schallmo et al., 2017). In terms of Agenda 2030 and its SDGs, waste, energy, economy, and environment are essential pillars that must be addressed. The new digital technologies may significantly contribute to the achievement of the SDGs, such as SDG2 "zero hunger" and SDG12 "responsible consumption and production," helping companies increase food production and profits, as well as reduce GHG emissions, energy, and resource consumption, thanks to greater efficiency of operations across the whole supply chain (Ejsmont et al., 2020). In agriculture, the I4.0 paradigm can help the poor people by providing more basic resources and services, promoting sustainable agriculture and sustainable food consumption and production systems, providing new technologies for clean drinking water and sanitation, and fighting climate change (Režek Jambrak et al., 2021). I4.0 technologies may boost efficiency in the agri-food supply chain, particularly for perishable goods (Vernier et al., 2021), by lowering costs, improving accuracy, speeding up procedures, lowering food's carbon footprint, and reducing FLW (Amani and Sarkodie, 2022). Finally, sustainable development assumes that farmers' welfare must be protected, their living standards must be improved, and the connection between urban and rural populations must be maintained (Eashwar and Chawla, 2021). Thanks to I4.0, farmers may use IoT-based drones to regulate water distribution and pesticide irrigation from their homes (Patel and Doshi, 2020), thus improving crop yield and quality of life.

Despite the potential highlighted benefits of I4.0 in agriculture, agribusinesses are still struggling to implement key digital technologies worldwide, primarily due to a lack of modernisation and automation necessary to implement this new technological paradigm (Konur et al., 2021). In addition, the possibility of integrating digital technologies and CE practices to prevent and reduce FLW at each point of the agri-food value chain, improve agribusinesses' environmental performance, and increase consumer awareness towards FLW issues has yet to be fully investigated (Lopes de Sousa Jabbour et al., 2018; Abbate et al., 2023a). These aspects lay the ground for different investigations on the topic, which have been addressed in this doctoral dissertation with the primary aim of empirically evaluating the environmental benefits of a circular and digitised agri-food supply chain, contributing to both theory and practice in the field. Notably, from the theoretical perspective, this research aims to extend the Institutional theory and Resource-based view theory by shedding light on the primary external and internal driving forces leading agribusinesses to embrace the digital and sustainable transition. Further, this research extends the Theory of planned behaviour by highlighting the leading factors affecting consumers' attitudes and intentions not to waste food. From the practical standing point, this research quantitively tests the impact of key digital technologies and CE practices on sustainable consumer behaviour, demonstrating how the implementation of such tools can not only reduce the environmental implications upstream of the agri-food supply chain but also downstream at the households' level. In addition, this research quantitively evaluates and compares the environmental effects of different CE initiatives employed by agribusinesses, thus suggesting the most beneficial solution for the environment compatible with companies' economic and financial constraints. Notably, the next Chapter analyses in more detail the innovative contributions of this doctoral thesis, presenting the research gaps identified and the research objectives addressed. Chapters 3 and 4 present a systematic and bibliometric literature review on digitalisation and sustainability trends in the agri-food industry. Chapter 5 contains a multiple case study analysis regarding the impact of I4.0 technologies and CE practice on FLW across the agri-food value chain. Chapter 6 presents a Life

Cycle Assessment (LCA) in the egg industry, evaluating the environmental impact of the intermediate stages of the value chain and demonstrating how the implementation of CE initiatives can lower the environmental damage. Chapter 7 contains a quantitative survey to determine the influence of digital tools and CE initiatives on consumers' attitudes and intentions not to waste food. Finally, Chapter 8 presents the thesis' general conclusions, highlighting in detail the practical and theoretical contributions of the research.

2. Literature review

Due to the significant increase in studies related to I4.0 and sustainability in the agri-food sector, some researchers previously reviewed the literature on the topic from different perspectives. For instance, Eichler Inwood & Dale (2019) identified numerous software applications enabling farmers to recognise business performance-enhancing activities. Notably, Kamble et al. (2020) summarised the influence of big data analytics on farming companies' supply chain, while Sarkar et al. (2020) explored some technologies to mitigate the negative effects of farm production and various crop simulation models for predicting agricultural production under changing climatic circumstances. On another note, Gonzalez-De-Santos et al. (2020) summarised the various architectures for robotic manipulators and mobile robots and the latest techniques used in smart factories. Further, Portanguen et al. (2019) examined the additive manufacturing technology for developing food biobased goods. Other researchers highlighted the benefits of digitalisation in the food sector to enhance efficiency, transparency, and sustainability (Raheem, 2020; Corallo et al., 2020), while Annosi et al. (2020) investigated significant obstacles for the development of digital technologies by agri-food companies. Other studies provided an overview of a range of new enabling technologies (e.g. blockchain, big data analytics, and RFID) which could further reduce food waste and the carbon footprint and increase crop yields, bioenergy generation and farm economic efficiency (Wolfe & Richard, 2017; Vågsholm et al., 2020). In addition, other studies have used professional sources and academic ones to contribute to the debate on how the new I4.0 technologies affect the agri-food sector. Notably, Secinaro et al. (2021) conducted a content and thematic analysis of both scientific papers collected from the Scopus database and patents obtained from the European Patent Office (EPO) dataset to explore how the enabling I4.0 technologies (such as artificial intelligence, machine learning, and augmented reality) can promote agri-businesses. Similarly, Trappey et al. (2017) employed a systematic approach to highlight how IoT technology standards and patents can be used as critical enablers for advanced manufacturing in the I4.0 context and different sectors, such as agriculture and hospitality. Finally, Trappey et al. (2016) offered a comprehensive review of the most recent CPS literature and a thorough examination of international standards and patent portfolios relating to the CPS architecture, with applications in different contexts such as healthcare and agriculture.

However, the scientific literature lacks a study that holistically summarises the impact of I4.0 on sustainability in the agri-food sector and evaluates research progress and trends on the topic to benefit multiple stakeholders. In addition, general literature reviews on the relationship between I4.0 and sustainability (e.g., Piccarozzi et al., 2022; Beltrami et al., 2021; Ghobakhloo et al., 2020; Machado et al., 2020; Ciano et al., 2019; Kamble et al., 2018) do not cover the specificities of the agri-food industry. It is worth to note that literature reviews can be conducted using different methodologies, such as structured and bibliometric literature reviews. The structured (or systematic) literature review evaluates a body of academic literature to generate insights, critical reflections, future research directions, and research questions (Massaro et al., 2016). However, the growing number of studies published every year made systematic review studies impossible to perform in a reasonable amount of time. As a result, researchers more recently developed various software packages for semi-automating the examination process using machine learning (ML) and algorithms for text mining, significantly enhancing and speeding up the systematic review process's efficiency (Cleo et al., 2019). The adoption level of these resources nowadays appears to be limited (Altena et al., 2019). As far as we know, no one has adopted these tools to provide relevant knowledge concerning I4.0 and agri-food sustainability and show the research field's evolution. Further, the application of the ML tools allowed us to overcome the biases due to the manual selection of the systematic review process. On another note, bibliometric analysis is a technique for rigorously studying and evaluating vast amounts of scientific data, enabling researchers to grasp the evolutionary intricacies while also shedding light on emergent areas (Donthu et al., 2021). The literature lacks a bibliometric literature review on the topic investigated, which is particularly useful for identifying the research field structure. Indeed, this analysis provides a clear picture of the leading authors, journals, articles, and themes, further proposing emerging research clusters, encouraging researchers to collaborate and share knowledge in the research field (Mishra et al., 2018). To overcome these limitations, the first objective of this Ph.D. thesis was to perform a comprehensive overview of I4.0 and sustainability in the agri-food sector using advanced tools and algorithms, as well as bibliometric techniques, thus supporting researchers, policymakers, academicians, practitioners, farmers, and other decision-makers in exploring the complex domain of I4.0 in support of sustainable agriculture and suggesting further research directions on the topic. The diversity of methods reduces the risk of systematic errors or biases that could be introduced by a single methodology (Zaltman, 1997). Therefore, we performed a thorough review of the literature on the topic by adopting and integrating both systematic and bibliometric analysis, which overcame the shortcomings of the two techniques used separately. As a result, we first aimed to answer to the following research question (RQ):

RQ1. *How is digital transformation affecting the agri-food sector?*

The systematic and bibliometric analysis of the literature uncovered a dearth of knowledge and research about the potential application and integration of digital technologies and green practices to address the agri-food sector's sustainability challenges, and the few studies conducted have produced divergent results. Therefore, a multiple case study was subsequently conducted to explore the practical ways of how I4.0 and CE can be best employed in the agri-food supply chain for FLW mitigation. The sustainable and technical development of agribusinesses would be aided by this integration, leading to successful corporate operations and environmental protection. In addition, the existing empirical research on green innovation and supply chain management focuses primarily on theory testing, examining the relationships between isomorphic pressures, internal resource intensity, green supply chain management practices (GSCM) implementation, and corporate performance (e.g. Saeed et al., 2018; Ueasangkomsate and Pornchaiwiseskul, 2019; Zhang et al., 2020; Sobaih et al., 2020; Niazi et al., 2023). Notably, some studies used institutional pressures as moderating factors to investigate the link between GSCM practices and corporate outcomes (e.g. Zhu and Sarkis, 2007; Kalyar et al., 2019). Further studies examined the moderating effect of the enabling I4.0 technologies on the links between institutional forces, GSCM practices, and business performance (e.g. Bag et al., 2022; Shahzad et al., 2022). Therefore, there is a lack of theory-building studies investigating how external and internal driving factors are shaping the structure of the current supply chains to foster green innovation and fulfil the emerging demands of digitalisation and sustainability. Indeed, firms are under increasing pressure towards social and environmental responsibilities for their products, both upstream and downstream of the supply chain (Centobelli et al., 2022; Abbate et al., 2023b). In addition, prior empirical research has primarily focused on individual agribusinesses (e.g. Goonan et al., 2014), ignoring the processes involving other players along the food value chain to mitigate FLW. Based on the above premises, by employing a qualitative data analysis of 20 purposefully selected Italian agri-food firms belonging to different value chain stages and under the lens of Institutional theory and Resource-based view theory, the second RQ this thesis seeks to answer is:

RQ2. *How are agribusinesses redesigning their supply chain to fulfil increasing stakeholder demands for effective food loss and waste mitigation?*

In addition, the comprehensive analysis of the literature highlighted a lack of studies comparing various sustainable and circular practices to determine which is best for the environment, minimising waste of food and resources and promoting the agri-food industry's circularity. With the goal of pushing the envelope of environmental sustainability even further, it is essential to discover methods to connect sustainable supply chain strategies with CE principles and quantitively recognise the associated environmental advantages (Nasir et al., 2017). The CE also tends to be associated with economic systems' material flows as a result of a paradigm shift in business model, leaving the analysis of environmental and social impacts, for example, those related to energy use, carbon emissions, employee welfare, food safety, and food security, unaddressed (Genovese et al., 2017). An egg industry case study was used to shed light on these challenges. This sector was chosen for its unique characteristics. First, the egg industry is expanding rapidly, thus requiring increasing attention from the environmental sustainability perspective: in the last decade, the worldwide egg industry has been growing at a rate of 2.8% per year, producing approximately 70 million tonnes of eggs annually (Pelletier, 2017). Therefore, egg production is considered one of the fastest-growing industrial livestock industries, especially in countries where income and individual purchasing power have increased significantly (Turner et al., 2022). In addition, egg production has a lower environmental impact than other protein-rich foods such as meat; diversification of protein sources, focusing on sustainable egg production, is essential to address global food security and environmental challenges (Mottet and Tempio, 2017). Hens convert their feed into eggs more efficiently than raising animals for meat production, thus playing a key role in mitigating the environmental impact associated with the food industry. Further, hens can convert food and agricultural waste into eggs, thus helping to reduce the amount of organic waste by turning it into valuable food (Mottet and Tempio, 2017). The eggs are also recognised as healthy and balanced food, and they have been particularly appreciated since the COVID-19 pandemic began, and attention to health has become a priority (Malone et al., 2021). Further, compared to other foodstuffs, egg production can be done by raising hens on a local scale, thus reducing the need for long supply chains and minimising the environmental impact associated with transporting food over long distances (Costantini et al., 2020). Therefore, by employing the LCA methodology, the next objective of this doctoral thesis was to evaluate the environmental impacts related to the intermediate phases of the egg supply chain, mainly associated with the packaging, inner and outer logistics, and distribution, and identify the CE initiatives to reduce the environmental implications.

The LCA methodology has already been used to investigate egg supply chains in different geographical settings (e.g. Leinonen et al., 2012; Wiedemann and McGahan, 2011; Dekker et al., 2011; Vergé et al., 2009; Mollenhorst et al., 2006). However, in the scientific literature, there is little knowledge on the comparison of different CE strategies to choose the potentially beneficial solution for the environment and society by employing the LCA approach. Furthermore, there is no evidence of this kind of analysis from the Italian egg industry, which is one of the largest egg markets in Europe, with an average annual consumption of 189 eggs per inhabitant (Rondoni et al., 2021). In this view, a recent contribution has underlined country-specific analysis's crucial importance in adopting effective policy measures to face the FLW (Nicastro and Carillo, 2021).

Based on the above premises, the third and fourth RQs this study aims to answer are:

RQ3. *What are the environmental impacts of the intermediate phases of the egg industry supply chain?*

RQ4. *What circular economy strategies can be implemented to reduce the environmental implications of the egg industry supply chain?*

Finally, once determined the key technologies and practices leading to improve agribusinesses' environmental performance, the final objective was to test the influence of such tools on consumers' attitudes and intentions not to waste food. Notably, current research on consumers' sustainable behaviour towards food waste and the factors influencing food waste mitigation is mainly focused on investigating the households' actions and attempts to reduce food waste generation, for example using shopping lists, avoiding purchasing more foodstuff than necessary, paying more attention to the expiration date, or reducing the food portion size (e.g. Stefan et al., 2013; Ponis et al., 2017; von Kameke and Fischer, 2018; Janssens et al., 2019; Lorenz-Walther et al., 2019; Amato et al., 2021). Although, there is a dearth of papers investigating the effect of CE practices and enabling technologies adopted by agribusinesses (i.e. sustainable labelling, knowledge of foodstuffs traceability, sustainable packaging, and local food supply) on households' attitudes and intentions towards the reduction of food waste. For instance, quick response (QR) codes with traceability labels have recently been put on product packaging to make it simple for customers to retrieve traceability information, increasing their propensity towards sustainable food purchasing choices (Spence et al., 2018). Based on the above premises, by employing a quantitative survey involving 283 Italian food consumers and under the lens of the Theory of planned behaviour, the final RQ this study aims to answer is:

RQ5. *What circular economy practices and technological innovations adopted by agribusinesses exert influence on consumers' behavioural intention concerning food waste reduction?*

Figure 1 highlights the overall research plan, showing the objectives of the thesis, the Chapters in which each RQ is addressed, and the respective research methodology employed.

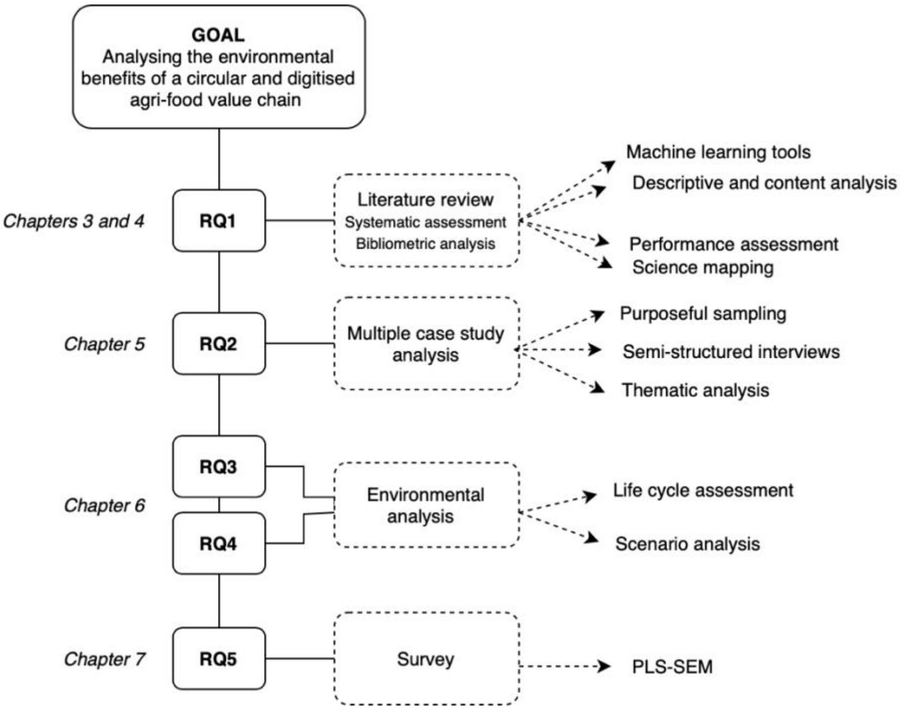


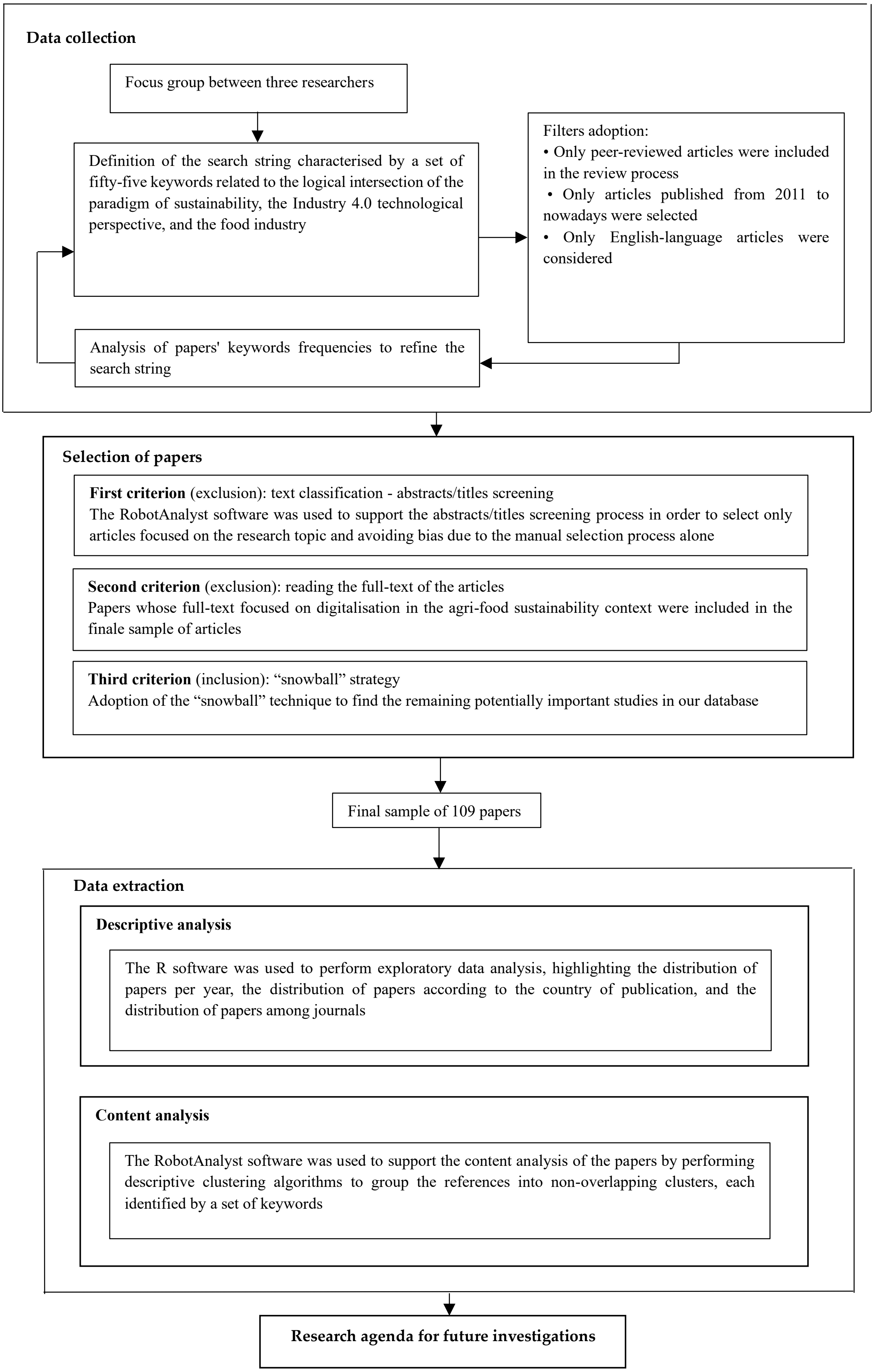
Figure 1. Research Plan

3. The digital and sustainable transition of the agri-food sector

Recent forecasts indicate that food production will need to double by 2050 to meet the world's growing population's estimated demand and that the world expects approximately 9.8 billion people to live in 2050 and 11.2 billion by 2100 (Ojo et al., 2018). The world's expected population growth will undoubtedly result in increased waste generation and its environmental effect (Belaud et al., 2019). To address these issues, agri-food companies have begun implementing different digital technologies to increase food production while utilising fewer resources, thus reducing production processes' environmental impact. This Chapter aims to answer the first RQ presented in the previous Chapter (i.e. *How is digital transformation affecting the agri-food sector?*) by systematically reviewing I4.0 and agri-food sustainability research published in the last decade, highlighting research progress and trends on the topic for the benefit of multiple stakeholders. Text classification and data extraction machine learning techniques have been used to support the literature review process. Notably, text classification was used to support the screening phase of titles and abstracts, while data extraction was used to support the content analysis phase by identifying the main topics on which documents are focused. The descriptive analysis shows a summary of the leading scientific journals in the research field, as well as the most influential countries and the research topic evolution over time. The content analysis allowed us to identify ten main research clusters, providing in-depth discussions and perspectives on critical areas for future research avenues. The results of this investigation will help agri-food firms transition to a digitalised, sustainable business model, resulting in advantages for themselves and society. To achieve this result, agribusiness firms' leaders have totally rethink how they operate, develop innovative strategies, and create sustainable digital business models from both an economic and social standpoint. As a result, they should follow a logic that prioritises long-term, shared value creation over short-term efficiency and profitability. For instance, using I4.0 technologies may assist in minimising the use of resources, pollutants, and GHG emissions into the environment and regulate the impact of farming activities on soil and air quality. According to this viewpoint, businesses in the agri-food sector may provide long-term economic and environmental advantages while also improving their capacity to embrace efforts to combat climate change and avert the harmful effects of rising temperatures on the ecosystem.

3.1 Methodology

This section presents the literature review process, including the material collection and selection phases and text mining and ML techniques used to support the review process. Figure 2 highlights the steps of the proposed methodology, starting with the definition of the search string to the development of the research agenda for further investigation.



Data collection

Focus group between three researchers

Definition of the search string characterised by a set of fifty-five keywords related to the logical intersection of the paradigm of sustainability, the Industry 4.0 technological perspective, and the food industry

Filters adoption:
- Only peer-reviewed articles were included in the review process
- Only articles published from 2011 to nowadays were selected
- Only English-language articles were considered

Analysis of papers' keywords frequencies to refine the search string

Selection of papers

First criterion (exclusion): text classification - abstracts/titles screening
The RobotAnalyst software was used to support the abstracts/titles screening process in order to select only articles focused on the research topic and avoiding bias due to the manual selection process alone

Second criterion (exclusion): reading the full-text of the articles
Papers whose full-text focused on digitalisation in the agri-food sustainability context were included in the finale sample of articles

Third criterion (inclusion): “snowball” strategy
Adoption of the “snowball” technique to find the remaining potentially important studies in our database

Final sample of 109 papers

Data extraction

Descriptive analysis

The R software was used to perform exploratory data analysis, highlighting the distribution of papers per year, the distribution of papers according to the country of publication, and the distribution of papers among journals

Content analysis

The RobotAnalyst software was used to support the content analysis of the papers by performing descriptive clustering algorithms to group the references into non-overlapping clusters, each identified by a set of keywords

Research agenda for future investigations

Figure 2. Literature review process

3.1.1 Methods

We used RobotAnalyst to support the literature review process, in particular the abstracts/titles screening procedure and the content analysis phase (Przybyła et al., 2018). After manually screened a certain number of references, the RobotAnalyst ML algorithm was trained to predict the probability that an unlabelled citation should have been included. Notably, an inclusion prediction probability (0 to 1) was allocated to each unlabelled reference. Therefore, RobotAnalyst implemented an automated screening process to mark the remaining citations in the database. Notably, if the inclusion confidence of an unlabelled citation was minor than 0.5, it was excluded from the collection, otherwise it was included. In addition, in order to support the content analysis of the papers, the RobotAnalyst software provides an interface for descriptive clustering algorithms to group the references into non-overlapping clusters, each identified by a set of keywords. The keywords are automatically extracted, and they are chosen as the most descriptive group to discriminate the cluster references from other references. Each cluster is a group of similar references: the keywords are prevalent within the cluster, mainly located to the cluster, and cover the cluster's specific theme. Notably, spectral clustering is used to generate these groups. It works by applying the term frequency inverse document frequency (TF-IDF) weighting on the cosine similarities between a vector bag of words representing abstracts and titles, considering only words that appear at least five times in the collection and are not included in the stop-words list (Przybyła et al., 2018). Subsequently, a statistical selection method is used to determine a group of words describing each cluster concisely. More precisely, the algorithm selects cluster-related keywords primarily and uses then the conditional criterion for mutual optimisation of information to reduce redundancy. For each cluster, the number of keywords used is chosen using the Bayesian information criterion to statistical model order selection after a model has been designed to predict membership based on keyword presence. Finally, the keywords are sorted by their weights for each cluster (Przybyła et al., 2018).

3.1.2 Data collection and selection

The initial sample of articles was retrieved from the ISI Web of Science (WoS) database. More specifically, this study used the WoS Core Collection. WoS is a leading source of data compared with other academic databases (such as Scopus and Google Scholar) (Shashi et al., 2020c). Besides, the WoS comprises a wide variety of publications from various fields and study areas (Kamble et al., 2020; Aghaei Chadegani et al., 2013), including more than 15,000 high-quality journals and 50,000,000 articles, 251 research categories, and 150 subject areas for research (Shashi et al., 2020a; Gaviria-Marin et al., 2019). In addition, WoS offers a large set of metadata, including abstract, references, citation count, authors and institutions names, countries, and the journal impact factor

(Shashi et al., 2020b; Gaviria-Marin et al., 2019). Notably, we used the R software to analyse the huge metadata set and perform text mining algorithms, thus quickly providing different descriptive statistics. In addition, RobotAnalyst has combined text mining and ML techniques to the metadata set, allowing to semi-automate the abstract/title screening process and automatically extract data from article abstracts, supporting the content analysis phase.

The keywords used to collect data were defined after a focus group between three researchers and refined once the frequency of the keywords adopted by previous papers was analysed. In particular, we initially considered a set of keywords related to the logical intersection of the paradigm of sustainability, the I4.0 technological perspective, and the agri-food industry. The keywords used for I4.0 were retrieved from the framework proposed by Calenda (2016). We compared our keywords with those used in the individual articles discovered in the initial list to confirm our search string further. According to a keywords' frequency analysis, "digital platform*" and "intelligent system*" were found to be included in more than 10% of the publications. As a result, we included these keywords in the final search string:

(("Industry 4.0" OR "industry4.0" OR "industrie 4.0" OR "industrie4.0" OR "fourth industrial revolution" OR "4th industrial revolution" OR "industrial internet" OR "artificial intelligence" OR "cybersecurity" OR "cyber-security" OR "cyber security" OR "autonomous robot*" OR "cloud computing" OR "augmented reality" OR "virtual reality" OR "internet of things" OR "big data" OR "iot*" OR "additive manufacturing" OR "3d prin*" OR "rapid manufacturing" OR "advanced manufacturing" OR "intelligent system*" OR simulation OR "digital platform*" OR "machine learning" OR blockchain OR "block-chain" OR wearables OR "digital technolog*" OR "digital transformation" OR digitalization OR digitalisation OR "4.0" OR "digitization" OR "automation" OR "autonomous system" OR "robot" OR "cyber-physical" OR "phygital" OR "wearable" OR "sensor") AND ("environmental management" OR "sustainable operation*" OR "Environmental responsibility" OR "sustainable development" OR "triple bottom line" OR "circular economy" OR "environmental sustainability" OR "social sustainability" OR "corporate social responsibility") AND ("food" OR "agri-food" OR "agrifood" OR "agriculture")).

This search string, characterised by fifty-five keywords, was used to obtain documents containing those words in the title, abstract, or keywords. Moreover, the asterisk (*) was used to merge both singular and plural keywords.

The data search was conducted on 5th February 2021, and a sample of 673 documents was retrieved. We adopted different filters to refine our analysis. First, we decided to restrict the time frame analysed from 2011 to 2021 due to the actuality of the research topic (Desore and Narula, 2018). Indeed, the I4.0 concept first appeared in 2011 in a report diffused by the German government (Gajdzik et al., 2020). We also refined our investigation limiting the collection of data to English-language articles (Shashi et al., 2020c). Besides, to ensure the accuracy of the examined sources, we have agreed to strictly select articles and reviews published in double-blind peer-reviewed journals (Shashi et al., 2020b). Therefore, we excluded other sources such as conference proceedings, book series, extended abstracts, and reports. A sample of 466 papers was obtained after these choices. Subsequently, we adopted different exclusion/inclusion criteria described below.

As a first exclusion criterion for this study, we followed Pittaway et al. (2004) and carefully examined each paper's abstract to ensure that we only included research that specifically addressed digitalisation in the sustainable agri-food industry context. According to the RobotAnalyst semi-automated process, we obtained two lists of documents. List A includes papers whose abstract focuses on the impact of I4.0 technologies on the agri-food industry's sustainability performance. Thus, these papers focus on the paradigm of sustainability, the I4.0 technological perspective, and the agri-food sector. In contrast, list B includes articles whose abstract does not focus on the three dimensions simultaneously (mainly abstract that concentrates on sustainability in the agri-food sector but without any specific technological application). Before removing the articles included in list B (340), a sample check of about 20% of the excluded documents was carried out by reading the abstracts to verify that they really were not aligned with the topic. Further, the remaining 126 papers included in list A were subjected to the second exclusion criterion, which involved reading the full-text of the manuscripts. Two researchers examined the papers simultaneously, with a third researcher in case of any doubts (Cerchione and Esposito, 2016). The full-text reading allowed us to analyse the content of the articles in-depth and discard those not focused on the research topic. As a result of the second exclusion criterion, we excluded 28 papers. Finally, we employed a "snowball" technique as an inclusion criterion to find the additional potentially relevant studies (Greenhalgh and Peacock, 2005). Notably, snowballing is the process of finding new articles by looking through a paper's reference list or citation list. As a result of this inclusion criterion, we added 11 more papers on the subject. The final inclusion criterion ensured that all relevant studies were included in the final sample of articles. Consequently, the final sample includes 109 documents.

3.2. Descriptive statistics

Metadata extraction and analysis were performed to show papers distribution over time and provide essential information for future research summarising the most influential journals and countries in the research field. Different R packages for data science included in the tidyverse collection (e.g. dplyr and ggplot2) were used to perform exploratory data analysis, thus modelling, manipulating, and visualising data. As a result, the R software was used to transform a set of unstructured data into structured value-added data.

3.2.1 Distribution of papers by year of publication

The search for articles started in 2011, the year in which the concept of I4.0 appeared for the first time. As shown in Figure 3, the pattern of published papers exponentially increased to a maximum of 52 in 2020, thus highlighting a growing interest in the topic investigated over time. Figure 3 also reports the number of publications in 2021 (6) for completeness. Therefore, the distribution of papers emphasises that the field of I4.0 and sustainability in the agri-food industry is very recent: from 2019 to early 2021, about 70% of papers have been published. Notably, the attention of researchers seems to have arisen from the Hannover event "Agritechnica 2013", a leading fair for technical innovations in the agri-food sector. Furthermore, thanks to the extensive program of specialised international events, including congresses, meetings, and press conferences, Agritechnica is considered the most important forum for the future of the agricultural sector.

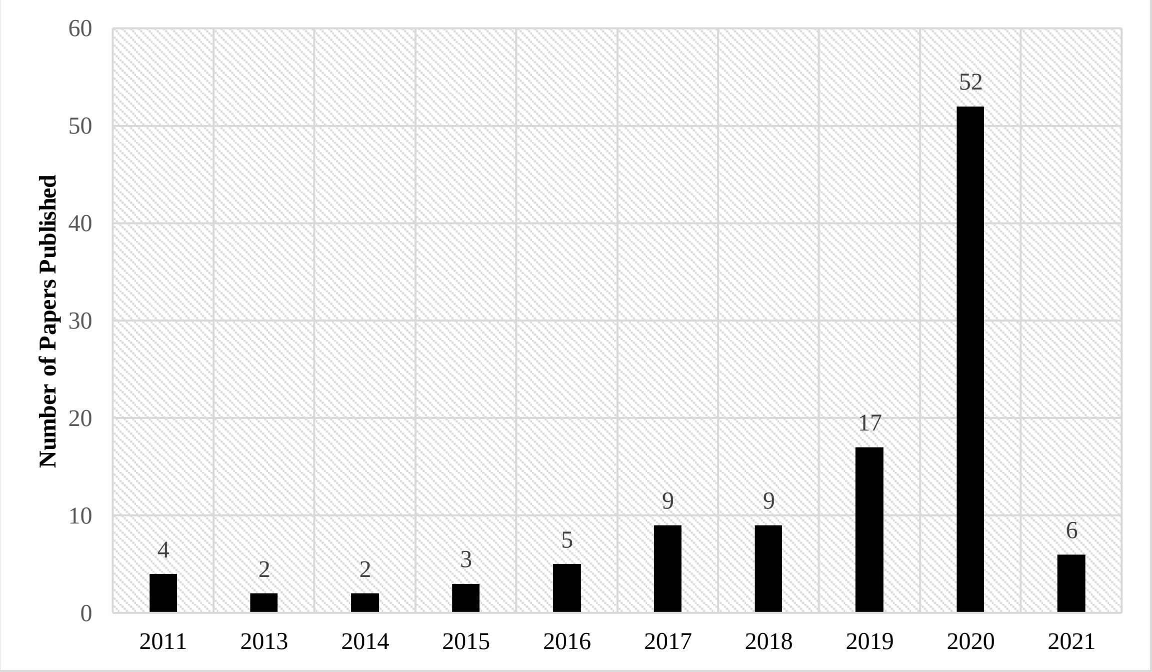


Figure 3. Paper distribution per year

3.2.2 Academic Journals

Considering the journals publishing in the research field investigated, it is interesting to highlight how the investigated topic is widespread in the literature. Indeed, the articles of our sample are available in 80 different journals. Notably, the journals that published at least two papers on I4.0 and sustainability in the agri-food sector from 2011 to early 2021 are shown in Figure 4. The most significant contributor is *International Journal of Production Economics* (6 papers), followed by *IEEE Access* (4 papers), *Sensors* (3 papers), *Remote sensing* (3 papers), *Journal of Cleaner Production* (3 papers), *British Food Journal* (3 papers), *Agronomy-Basel* (3 papers), and *Agricultural Systems* (3 papers). Looking at SCImago rankings to assess the scientific impact of each journal, all the outlets displayed in Figure 4 are in the Quartile 1 (Q1) excepting *Sustainability* (Q2), *British Food Journal* (Q2), *Foods* (Q2), and *Computers and Electronics in Agriculture* (Q2). The leading journals publishing on food sustainability and I4.0 have wider scopes and belong to different domains, confirming that the broader range of coverage I4.0 and sustainability issues have gained over the years.

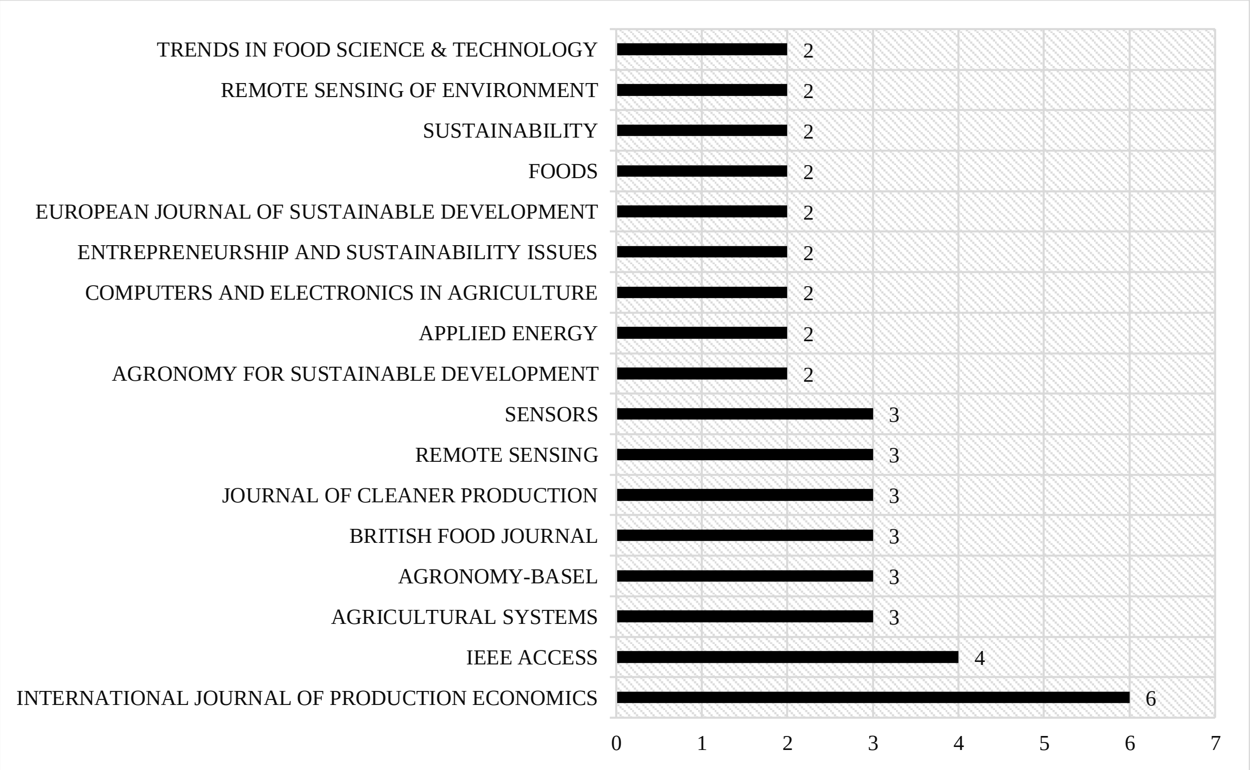


Figure 4. Number of papers per journal

3.2.3 Country analysis

Figure 5 classifies papers according to the country of the authors. Only countries with at least five papers published per each are reported. Notably, researchers from various nationalities co-authored some papers, as well as authors from the same country co-authored other papers. The country of each researcher who co-authored the article is counted in the first condition mentioned above. In the latter case, the nation is counted once even if two or more scholars co-authored the manuscript. The top contributing country is Italy (24 papers), followed by China (20 papers), and the United States of

America (USA) (16 papers). The first place of Italy is not unexpected because the Italian government in 2016 launched the "Italy: Industry 4.0" plan (Garzoni et al., 2020), i.e. the Italian national strategy for the digitalisation of industry. It includes a wide range of policy measures to stimulate international investment and innovation-driven economic growth.

Furthermore, according to Troise et al. (2021), agri-food is a major industry sector worldwide, particularly in Europe, which is at the top of the ranking concerning publication on I4.0 and sustainability in the agri-food sector since about 48% of the top publishing countries' papers displayed in Figure 5 are European. Besides, Figure 5 highlights the prominent role of both China and the USA in the I4.0 research. Indeed, even if the concept of I4.0 was built in Europe, China's economy launched in 2015 the "Made in China 2025", an initiative to turn China into a world-leading manufacturing force directly encouraging Germany's “Industry 4.0" strategy (Wang et al., 2020). Moreover, the USA has established an initiative called “A Strategy for American Innovation” to generate additional jobs and improve its Information and Communication Technology (ICT) leadership (Min et al., 2019).

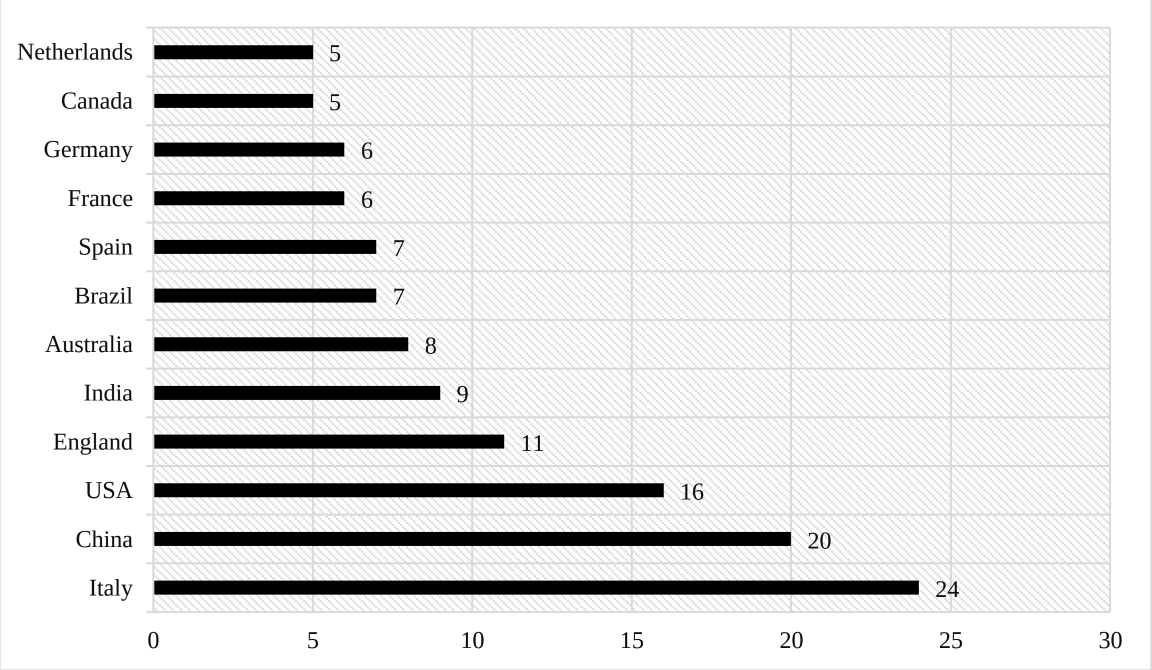


Figure 5. Papers classified by country

3.3 Cluster analysis

This section describes the RobotAnalyst-supported cluster analysis procedure. This technique aims to group references into different clusters, one for each theme covered, thus supporting and speeding up the content analysis of the papers. The results of this clustering process are reported in Table 1.

Table 1. References grouped into clusters by thematic area

Cluster 1: digitalisation and precision agriculture	***Cluster 2: remote sensing technologies in agriculture***	***Cluster 3: digital technologies to improve traceability and food safety***
technology, smart, digital, innovation, precision, technological, discuss, digitalization, theory	accuracy, monitoring, environmental management, sensor, sense, resolution, detection, learning, remote, image, satellite, random, square, datum	consumer, responsibility, product, healthy, diet, safety, intake, food sector, traceability, food system, nutritional, author, content, behavioural
Cluster 4: modern technologies to improve soil health and fertility	***Cluster 5: simulation models to predict energy consumption***	***Cluster 6: emerging technologies supporting agri-food supply chain management***
experiment, soil, yield, ha, crop, fertilizer, rice, cropping, farming, rotation, management practice	energy, electricity, renewable, emission, fuel, biofuel, cattle, production, simulation, system	supply chain, chain, supply, food supply chain
Cluster 7: advanced technologies used to reduce water consumption	***Cluster 8: digital technologies in support of the circular economy***	***Cluster 9: cloud-based platforms to acquire and manage data***
irrigation, water resource, groundwater, water, allocation, shortage, optimal, agricultural water	waste, circular, solid, recycle, recovery, treat, wastewater	ecosystem, trade-off, service, landscape, synergy, conservation, habitat, ecological, stakeholder, participatory, policy, land, epistemology
Cluster 10: the role of I4.0 technologies in mitigating climate change		
land use, climate, cover, forest, projection, land, km, change, period, regional, future, area		

3.3.1 Digitalisation and precision agriculture

Precision agriculture is a farm management strategy that uses information technology to acquire data that leads to decisions aimed at agricultural production. The aim is to match land and crop management with the specific needs of a diverse field to improve production, minimise environmental damage and raise the quality standards of agricultural products. It follows that precision agriculture techniques could minimise wasteful resource consumption and pollution and thereby increase the quality of life, which contributes to the achievement of sustainable development goals (Bhakta et al., 2019). In this regard, Clapp & Ruder (2020) examined the advancement of precision agriculture technologies - specifically digital farming and plant genome editing - and their consequences for environmental sustainability policies in the agri-food industry. Trivelli et al. (2019) examined how the two areas of I4.0 and precision agriculture are linked by examining the most widely applied innovations in both fields to identify similar trends and technical intersects. Dunchev (2019) conducted a survey to assess the cost-effectiveness of precision technologies in soft fruit production and explore the feasibility of implementing them. Almadani & Mostafa (2021) summarised new technologies used in the agri-food industry to improve productivity, optimise costs, and promote sustainable development. Further, they proposed a multimodal communication model that uses the

Data Distribution Service (DDS) middleware to coordinate communication among diverse production systems. As regard to precision fertilisation, Hüttel et al. (2020) used a rational action approach that included behavioural, social, and control dimensions to analyse intentions and actual use of sustainable digital fertilisation approaches. Giannoccaro et al. (2020) showed the development, construction, testing, and control of the dosage system of fluid and granular fertilisers with an innovative low-cost system to support crops and achieve more precise farming. Likely, Chen et al. (2014) proposed three precision fertilisation techniques: testing soil for formulated fertilisation technology, decision support system, and expert decision support system. Moreover, as mentioned above, the IoT is at the heart of intelligent agriculture, and it has the potential to reform and improve conventional agriculture to lower costs, reduce emissions, and boost efficiency and quality (Wu and Ma, 2020). Cloud computing systems and wireless networks are at the heart of the IoT since it collects data from sensor groups and uses decision analysis to modify object behaviour control and feedback (Cai et al., 2019). In this context, Kamienski et al. (2019) developed an intelligent water management platform based on IoT technology to provide the exact volume of water needed by crops. In order to monitor temperature, Cai (2019) designed a smart greenhouse control system based on both IoT and WSN technologies. Likely, Srbinovska et al. (2015) designed a useful and cheap greenhouse monitoring system based on WST. This architecture can monitor and regulate critical environmental parameters such as temperature, moisture, and lighting, based on various I4.0 technologies, including sensors and cloud, thus conserving natural resources, improving food quality, and lowering management and agri-business costs. As a result, these technologies can provide crops with the exact amount of resources they need, improving their fertility and avoiding waste and environmental pollution.

Other researchers systemically reviewed the literature on the topic of digitalisation in the agri-food industry. For instance, Annosi et al. (2020) reviewed the literature to investigate the most common obstacles for agri-food companies when it comes to using and adopting emerging technologies. On another note, Ciruela-Lorenzo et al. (2020) analysed the digital innovation advancement in agri-cooperatives to assist them in the decision-making phase. As a result, these developments can move agriculture closer to the idea of intelligent farms. Moreover, Rose et al. (2021) highlighted the importance of including social responsibility into the concept of agriculture 4.0, which has far-reaching social consequences, both positive and negative.

Other authors focused on quantitative studies. Bai et al. (2020) proposed a hybrid multi-situation decision method integrated by hesitant fuzzy set, cumulative prospect theory, and VIKOR to assess the impact of I4.0 technologies on food companies' sustainability performance. Carillo & Abeni, (2020) proposed a statistical two-stage regression method to quantify whether there is an intermediate productivity gap in herd management among agri-food companies with a different degree of digitisation adoption. This study utilised the outcomes of a survey in the Lombardy dairy farm (Italy). Finally, Thomas et al. (2018) conducted a survey, follow-up interviews, and visits to 32 food companies in the UK to investigate Smart Systems' applicability, defining the main priority dimensions and improvement levers for such a system's application.

3.3.2 Remote sensing technologies in agriculture

The increasing demand for food and energy supplies worldwide increases climate change risk due to higher agricultural GHG emissions. Therefore, it is widely acknowledged that agriculture should establish a new environmental sustainability framework that includes GHG emissions reduction (Julius Szakacs et al., 2011). In this context, remote science has developed more accurate, consistent, and reliable methods for capturing land dynamics to meet different knowledge needs (Olofsson et al., 2014). For instance, Szakács et al. (2011) used remote sensing systems to evaluate current and potential soil organic carbon (SOC) stocks in degraded pastures quickly and low-costly. Singh (2021) summarised various approaches to resolve environmental concerns about soil salinisation, highlighting different remote sensing techniques and geographic information systems used. Liu et al. (2020) used the Google Earth Engine cloud computing platform to develop a 30-m planetary-scale cropping intensity (CI) mapping application. CI was estimated using this method in eight geographic regions across continents that indicate global cropping system diversity from 2016 to 2018. Weiss et al. (2020) reviewed the leading remote sensing technologies used in agriculture for different scopes, such as agricultural land use monitoring and crop yield forecasting. Li et al. (2019) demonstrated a cloud-assisted mobile robot area control strategy in an intelligent greenhouse. Shen et al. (2019) developed and tested a robust drought monitoring model using deep learning methods based on multi-source remote sensing data in Henan Province, China. Holloway & Mengersen (2018) reviewed the literature on statistical machine learning techniques widely used for remote sensing data. The use of statistical analysis of remote sensing data to generate measurements of the environment, agriculture, and sustainable development has risen in popularity, resulting in increased cooperation between the earth science and statistical domains. Finally, Singha et al. (2017) analysed the usefulness of time-based characteristics extracted from gross resolution data for object-based paddy rice classification of fine resolution data. In order to increase classification accuracy, temporal features were extracted from the fused data and added using multi-spectral data. The temporal characteristics provided information about crop growth, while multi-spectral data provided the paddy rice pattern variation.

3.3.3 Digital technologies to improve traceability and food safety

Due to the recurrent cases of food-borne diseases, social sustainability aspects, such as public health, traceability, and safety, have gotten much attention in the agri-food sector. Digital technologies have high potential for improving these factors. First, Corallo et al. (2020) conducted a systematic literature review to investigate the relationship between food traceability and product lifecycle and highlight methods and technologies used by the food industry. Raheem (2020) reviewed the literature on digitalisation's advantages, highlighting that digital technology opportunities should increase the transparency, efficiency, and sustainable status of the local food business operators. On another note, Farooq et al. (2016) proposed an electronic pedigree traceability system based on integrating RFID and sensor technology for real-time agricultural food monitoring to prevent the distribution of dangerous and adulterated food items. Lin et al. (2017) proposed a blockchain-based ICT e-agriculture framework for both local and regional levels. This system increases farmers' access to high-quality data and agricultural services, enhances traceability, and certifies conformity with international standards. Notably, many precision agriculture developments, managerial support tools, and offering more access to clients rely on ICT (Bowen and Morris, 2019).

Different authors discuss the role of food-sharing platforms. For instance, Jæger & Mishra (2020) conducted a case study of the company-level IoT platform for seafood farmers that meets the end-to-end traceability demands of consumers while collecting data from downstream partners' information requests. Mazzucchelli et al. (2021) used multiple regression and fuzzy-set qualitative comparative analysis to highlight the effects and interactions between five factors that contribute to the success of food sharing platforms and their role in influencing consumer behaviour.

3.3.4 Modern technologies to improve soil health and fertility

This research cluster is mainly focused on models and strategies to monitor and predict crop yields and improve soil health and fertility. Shi et al. (2018) developed a variable-rate fertilisation model to improve fertilisation accuracy and uniformity. Gaydon et al. (2021) analysed the Agricultural Production Systems Simulator (APSIM) model, which has been able to simulate the performance of cropping systems from different perspectives, such as crop production and water consumption. Bhanarkar & Korake (2016) designed a wireless sensor network (WSN) for measuring and monitoring soil moisture and salinity. Miao et al. (2011) summarised different nitrogen management strategies that should be used to boost crop yields and reduce the environmental impact. Mandal et al. (2020) reviewed diverse simulation models and remote sensing techniques which have been used to forecast and map soil carbon status as well as define site-specific strategic policies to reduce the risk of land degradation and preserve environmental sustainability. Nasir Ahmad et al. (2020)

conducted a systematic literature review to investigate the soil erosion management methods that have been implemented and evaluated on agricultural land in Asia.

3.3.5 Simulation models to predict energy consumption

In I4.0 context, different simulation models have been used within the farms to predict energy consumption. In addition, these models can estimate the environmental impact of changes in infrastructure and management practices. Notenbaert et al. (2020) used the CLEANED model to evaluate livestock intervention with minimal environmental impact, improving incomes and food safety. Shine et al. (2020) summarised the milk energy research from the perspective of monitoring, modelling predictions and analysis. Vayssières et al. (2011) analysed the GAMEDE model, which was used to highlight the dynamics of the farm's key biophysical and decisional processes that influence labour, gross margin, and energy and nutrient flow in the farms.

3.3.6 Emerging technologies supporting agri-food supply chain management

It is well acknowledged that the new emerging technologies can support agri-food supply chain management. In this regard, Nosratabadi et al. (2020) reviewed the impact of new technologies on sustainable business model innovation of agri-food companies. The key factors that cause companies to innovate their business models have been identified in e-commerce and IoT technology. Kamble et al. (2020) proposed a framework for agri-food supply chain practitioners that recognises supply chain visibility and supply chain resources as the primary driving forces for improving big data analytics capability and achieving sustainable performance. Gružauskas et al. (2019) developed a collaborative technical strategy that encourages knowledge sharing to enhance forecasting accuracy and inventory management, allowing food demand and supply to be better aligned, thus reducing food waste. Machine learning algorithms are used in the forecasting process to provide supply chain participants with adaptation competencies. Ahearn et al. (2016) analysed the agri-food supply chain's main challenges in adopting big data to distinguish and classify final products based on underlying farm output attributes sought by supply chain consumers. Two examples demonstrate this, one considering using a sustainability metric and the other considering the possibility of increasing food safety. Dauvergne (2020) argued that productivity and efficiency increases obtained through AI in the middle parts of supply chains reverberate into more food production and consumption, benefiting big businesses even more than the environment's long-term viability.

3.3.7 Advanced technologies used to reduce water consumption

This cluster includes studies concerning new advanced technologies used to optimise water consumption. Mashaly & Fernald (2020) sheds light on studies concerning the use of System Dynamics (SD) and AI to better manage water use, highlighting limitations and challenges. Polinova et al. (2019) explored the Soil Water Atmosphere Plant (SWAP) model to optimise water management for cotton production. Zhou et al. (2019) proposed a holistic system-wide approach focused on water management perspectives that promotes small-scale hydropower generation while exploiting the synergies of the Water-Food-Energy (WFE) Nexus through artificial intelligence techniques. Adenugba et al. (2019) proposed an irrigation system that works based on sensors' environmental data using an IoT architecture. Data collected are used to predict environmental conditions such as humidity, temperature, and weather forecast used to manage the irrigation system.

3.3.8 Digital technologies in support of the circular economy

Regarding the relationship between I4.0 and CE, Cane & Parra (2020) conducted multiple case studies to explore the role of different mobile platforms in reducing food waste, thus contributing to circularity. Michelini et al. (2020) conducted two focus groups to examine the possible impact of food sharing platform business models in reducing food waste and the main barriers to calculate this impact. Fisher et al. (2020) explored how data-driven models can be used in the agri-food industry to promote the CE, process resilience, and waste valorisation principles. The growing availability of data is driving the increased use of data-driven models in manufacturing due to the introduction of low-cost industrial IoT technology, as well as increased processing capacity from cloud computing. Other studies focused on 3D printing applications. This new technology, also known as additive manufacturing (AM), now gives people a lot more flexibility to design, produce, and innovate in a variety of fields, including food production. Portanguen et al. (2019) reviewed the literature on AM in the food industry, showing that this new method could improve food safety and quality and reduce food waste. Lupton & Turner (2018) conducted an online discussion group to explore consumer behaviour on 3D printing applications concerning the production of laboratory-cultured meat or insect-based ingredients to promote ethical consumption and food safety. Furthermore, Sfragano et al. (2020) reviewed different printing technologies adopted for the sustainable production of sensors, including 3D printing and screen-printing, as well as the new eco-friendly materials proposed for these systems, such as cellulose and silk proteins. In the CE context, these innovative approaches and materials can ensure a reduced environmental footprint reducing the volume and the impact of waste coming from these processes.

3.3.9 Cloud-based platforms to acquire and manage data

Recent research acknowledged that applying geospatial Decision Support Systems (DSS) is a feasible and efficient tool for acquiring and managing data. Manna et al. (2020) demonstrated how a new type of DSS built on the open-source Geospatial Cyberinfrastructure (GCI) platform could serve as a critical web-based operational tool for olive farming by better connecting productivity and environmental sustainability. This system allows for the collection, management, and processing of data (e.g., pedology, everyday climate) and data visualisation and machine on-the-fly applications for simulation modelling (e.g., assessment of bioclimatic indices). Likely, Terribile et al. (2017) used a geospatial DSS developed on the GCI platform to improve the quality of viticulture by better-linking agriculture and landscape levels. The GCI platform enables the collection, management, elaboration, and on-the-ground simulation modelling of static and dynamic information (e.g. pedology, daily climate, and wine distribution), data view, and on-the-fly computer applications (e.g. grapevine water stress, and evaluation of ecosystem services).

3.3.10 The role of Industry 4.0 technologies in mitigating climate change

This research cluster focuses on the relationship between climate change and agri-food production and the role that technologies play in mitigating global warming. Notably, Bhaga et al. (2020) reviewed recent applications to assess the impact of climate variability and droughts on water resources in sub-Saharan Africa using remote sensing technologies. On another note, Sarkar et al. (2020) analysed low input sustainable agriculture techniques to boot agri-food production in a warming world.

3.4 Research agenda for further investigation

The descriptive statistics provided a broad overview of the articles included in the literature review, emphasising that, in recent years, there has been a growing focus on I4.0 and sustainability in the agri-food industry and that these subjects have a variety of scopes, belong to different disciplines and countries, and are covered by different journals.

On another note, RobotAnalyst software was used to support the content analysis of the selected articles, identify the literature's strengths and weaknesses, and highlight current research and future research directions. As a result, the selected papers can be classified into four main research areas: 1) Agriculture 4.0; 2) Circular economy; 3) Supply chain management; and 4) Simulation models. Table 2 displays a more in-depth description of current research and future study proposals for each of these scientific clusters.

Table 2. Current research and future research directions

Research area	Current research	Future research suggestions
Agriculture 4.0	1. Development of digital technologies to improve food quality and productivity, reduce resource consumption, and promote sustainable development 2. Application of remote sensing technologies for land use monitoring and crop yield forecasting	1. Development of multiple case studies to analyse: a. the impact of Industry 4.0 on sustainability performance b. the impact of digital technologies and circular economy practices on food loss and waste reduction c. drivers and barriers for the implementation of Industry 4.0 and sustainability 2. Longitudinal analysis to monitor the efficacy of digital technologies over time
Circular economy	1. Development of digital platforms to reduce food waste 2. Application of data-driven models to promote circular economy 3. Application of 3D printing to reduce waste	1. Application of the Life Cycle Assessment (LCA) methodology to estimate: a. the environmental impact of alternative Industry 4.0 technologies and sustainable/circular practices b. the environmental impact of food production before and after the implementation of technological solutions 2. Investigation of factors affecting foodstuffs' sustainable consumer behaviour through surveys
Supply chain management	1. Application of big data and artificial intelligence techniques to improve supply chain efficiency 2. Development of traceability systems to ensure the supply chain transparency	1. Analysis of the strengths and weaknesses of blockchain platforms for sustainable agri-food 2. Development and implementation of blockchain-based systems and Internet of Things (IoT) architectures for the agri-food value-chain traceability
Simulation models	1. Use of simulation models to monitor and predict crop yields, resource consumption, and soil carbon status 2. Use of simulations models to estimate the environmental impact of changes in infrastructure and management practices	1. Development of simulation models to determine the best management practices for enhancing carbon storage in the soil and increasing soil health and fertility

3.4.1 Agriculture 4.0

The first research area discusses the concept of agriculture 4.0. This term indicates the industry's significant trends, including a more accurate focus on precision agriculture, artificial intelligence, IoT, and big data use to drive increased corporate efficiency in the face of increasing populations and climate change (Gonzalez-de-Santos et al., 2020). In this context, current research is focused on developing and applying specific technologies in agriculture to monitor and boost crop yields, save natural resources, and promote sustainable development. However, there is a lack of an in-depth study with a holistic perspective that evaluates the impact of different digital technologies (e.g. blockchain, internet of things, and big data analytics) on the sustainability performance of the agri-food industry. Even if the use of advanced information technology in the agri-food sector was recommended many years ago and argued to be necessary for businesses to survive in the long term, there is little research and knowledge regarding how I4.0 technologies could be used to address the agri-food industry's sustainability challenges, and the few studies in the literature reveal conflicting results. It would also be interesting to investigate what CE strategies and I4.0 technologies are being applied at each point in the agri-food supply chain to reduce FLW. Therefore, future research could conduct multiple case studies through direct interviews with companies adopting I4.0 technologies and sustainable practices to analyse the relationship between I4.0 and sustainability and understand better benefits, barriers, and motivations for their implementation. Furthermore, by conducting a long-term longitudinal study, it is possible to observe the effectiveness of I4.0 technologies over time. Through this exploratory research will be possible to assess whether the changes in the way business models are structured in terms of technological innovations lead to better organisational economic, environmental, and social performance. Indeed, according to Brenes et al. (2016), business models are set-ups that have an impact on a company's success or failure.

3.4.2 Circular economy

The second research area concerns the CE, which can be defined as a regenerative system that minimises resource usage and waste, GHG emissions, and energy leakage by decelerating, closing, and narrowing material and energy loops (Miranda et al., 2021). In the context of sustainable agri-food and I4.0, the extant research is focused on the ability of the digital technologies to reduce waste of resources and food. Indeed, unlike previous industrial models, characterised by linearly producing waste, I4.0 seeks to minimise or eliminate waste, promoting circularity (Lopes de Sousa Jabbour et al., 2018b). Thanks to new technologies, it is possible to monitor resources and keep waste production under control, improving the operational performance of a sustainable supply chain (Ejsmont et al., 2020). However, there is a lack of studies that compare different I4.0 technologies as well as sustainable and circular practices to choose the most beneficial solution for the environment, thus reducing waste of food and resources and contributing to circularity. Therefore, we propose shared best practices based on CE tools to define sustainable paths for companies in the agri-food sector. Therefore, future investigations could use the LCA methodology to estimate the environmental impact of alternative digital technologies and sustainable practices used for food production. Furthermore, it is also possible to estimate the environmental impact of food production before and after implementing technological solutions to assess whether they have contributed to reducing the waste of food and resources as well as CO_2 emissions. The LCA represents a great tool to support the CE, as it allows for the calculation of the total environmental impact of all stages of a product's life cycle, thus identifying the inefficiencies and reducing the waste of resources (Nasir et al., 2017). Finally, future research could investigate factors affecting foodstuffs' sustainable consumer behaviour. Indeed, by carrying out surveys on the primary factors influencing consumer behaviour regarding food waste, such as sustainable packaging and labelling, as well as blockchain-based QR codes for food traceability, companies will be able to leverage those factors to foster a more sustainable production and consumption model. In addition, by investigating the driving factors affecting consumer behaviour towards food waste, policymakers for sustainable food consumption could develop consumer awareness programs to help achieve SDG 12 (Rasool et al., 2021).

3.4.3 Supply chain management

The third research area concerns supply chain management. This cluster discusses different digital technologies (e.g. RFID systems, big data, and artificial intelligence) used in the agri-food industry to ensure the traceability of products and improved efficiency of the entire supply chain. According to Kamble et al. (2020), blockchain is a powerful enabler of a sustainable agri-food supply chain, as it improves the transparency of information (Fu et al., 2018). However, the use of blockchain technology in the agri-food sector is still in its early stages (Stranieri et al., 2021). Few articles in the scientific literature analyse the development and implementation of blockchain-based systems supporting smart agriculture traceability. Moreover, since consumers are increasingly concerned about food quality and safety (Shahid et al., 2020), blockchain could help address traceability issues while ensuring sustainable development (X. Li et al., 2020). This new enabling technology has the potential to solve several issues relating to consumer concerns of the products they purchase (Borrero, 2019). Nevertheless, there are still unresolved concerns and challenges with blockchain technology that require further inquiry and investigation (Ali et al., 2021). As a result, future research could analyse the strengths and weaknesses of blockchain-based systems for sustainable agri-food and develop new blockchain and IoT architectures for agri-food traceability. The decentralised and secure nature of blockchains make it an ideal technology for communication between the individual nodes of an IoT network. These architectures could then allow the consumer to become part of the company's decision-making process, such as intervening and producing changes in the crop production process.

3.4.4 Simulation models

Finally, the fourth research area concerns simulation models. In particular, current research is mainly focused on applying these models to simulate crop production, resource consumption, soil carbon status, as well as to model the effects of a farmer's daily management decisions on the farm's overall sustainability. Consequently, future research could develop and apply simulation models that may be used to assess the best agricultural management strategies for enhancing carbon storage in the soil and increasing soil health and fertility.

3.5 Conclusions and implications

3.5.1 Contribution to theory

This paper provides a unique contribution to the literature on I4.0 and sustainability in the agri-food sector since it expands previous studies in diverse original ways, thus making relevant theoretical contributions.

Firstly, the study offers a broad systematic overview of I4.0 and sustainability in the agri-food industry, further evaluating the topic's evolution over time and providing essential information for future research summarising the most influential journals and countries in the research field.

Secondly, this analysis goes beyond the systemic review of literature by using automation tools and techniques for selecting the most relevant works and the critical subjects analysed by authors in the field. Notably, text classification and data extraction are the ML techniques used to automate this research. Text classification is used to screen title and abstract, while data extraction is used to identify the main topics on which the sample of documents is focused, thus grouping the articles into 10 research clusters, i.e. “digitalisation and precision agriculture”, “remote sensing technologies in agriculture”, “digital technologies to improve traceability and food safety”, “modern technologies to improve soil health and fertility”, “simulation models to predict energy consumption”, “emerging technologies in the current agri-food supply chain”, “advanced technologies used to reduce water consumption”, “digital technologies in support of CE”, “cloud-based platforms to acquire and manage data”, and “the role of I4.0 technologies in mitigating climate change”. As a result, the systematic review process allowed us to identify the major challenges in the field, highlighting the crucial role of the new digital technologies in improving agricultural and food production through monitoring, modelling, and optimisation of operations.

Moreover, this study offers a reference point for future research, emphasising potential new areas of investigation for both quantitative and qualitative studies. Notably, our research highlighted the enabling technologies that should be further investigated in the agri-food sector, such as the blockchain. Indeed, blockchain is a relatively new technology that is expanding rapidly, achieving new business areas. Even in I4.0, blockchain technology plays an increasingly important role in developing efficient and sustainable supply chain management (Zhang and Chen, 2020). High traceability and transparency, fewer errors and delays, accelerated problem detection, enhanced customer and partner trust, lower transportation costs, and better product transportation are just a few advantages of blockchain technology adoption (Centobelli et al., 2021). Thus, the potential for applying blockchain-based platforms in the agri-food supply chain is huge (Borrero, 2019) and should be better explored (Ali et al., 2021). In addition, scholars could conduct long-term longitudinal studies to observe the effectiveness of I4.0 technologies over time. On the other hand, quantitative researchers could focus on conducting surveys and investigating the factors affecting sustainable consumer behaviour towards foodstuffs, such as sustainable labelling and the use of blockchain technology to track and trace the product during its lifecycle.

3.5.2 Implications for policymakers and agribusiness firms

This research offers multiple opportunities to public authorities, organisations, and practitioners to leverage digital technologies' advantages in the agri-food sector. This paper therefore presents a wide range of relevant knowledge concerning how I4.0 technologies are affecting agri-food companies. Such overview is essential for agribusiness firms' managers since it allows them to innovate their business models and solve critical problems exploiting the potentials of this new technological paradigm. This work helps managers analyse the current state of I4.0 in the agriculture and food industry regarding innovations, technology, and assessment, to make appropriate decisions about using these tools and enhance sustainable environmental efficiency. As a result, the findings of this study suggest a substantial transition in the workforce in the imminent future, with more complex, software-related occupations being created. At the same time, more routine employment is being replaced by robots or comparable technology. This suggests that the labour market will fundamentally alter its structure, having a significant influence not just on a country's economy but also on potential offshore and outsourcing decisions made by businesses and, ultimately, on the structure of global trade. Agribusiness companies need to radically reassess their operations, develop strategies that are not business as usual, and create resilient digital business models from both an economic and social perspective. In order to connect with the numerous partners that make up the external ecosystem, for instance, businesses may need to rebuild their supply chains from the perspective of value creation for society as a whole rather than value appropriation for the firm itself. Adopting a social vision requires agri-food firms to recognise that the transition to such digitalised, sustainable business models results in advantages for both themselves and society. For instance, using precision agriculture technologies based on IoT may assist firms in boosting crop efficiency and productivity and minimising resource consumption by providing crops with the exact amount of water and fertiliser they need. Therefore, agri-food firms can regulate the impact that farming activities have on soil and air quality, avoiding overlapping passes by tractors and reducing the use of pollutants and the emission of CO_2 gases into the environment. In addition, agribusiness managers can employ new technological tools like blockchain to accomplish the sustainable goals of improved transparency and traceability of agri-food products in the supply chain, reducing FLW while lowering costs, decreasing the risk of mistakes and fraud, and speeding up procedures. According to this viewpoint, businesses in the agri-food sector may provide long-term economic, environmental, and social advantages while also improving their capacity to embrace efforts to combat world hunger and climate change and avert the harmful effects of rising temperatures on the ecosystem.

Furthermore, this paper also has significant policy implications. The seventeen SDGs highlight the seriousness and breadth of today's sustainability concerns (Sauermann et al., 2020). Moreover, the estimated increase in food demand in the next few years and several issues related to environmental pollution and global warming will require great attention from institutions and stakeholders. Therefore, this research has significant repercussions for regional and national growth. Policymakers and governments working on sustainable agriculture initiatives should use our study's findings to promote and implement digital technologies in the agri-food supply chains to improve crop yield, minimise carbon footprint, and promote sustainable development. For instance, policies implemented by the governments may include incentives and subsidised loans for farmers to purchase new machinery and green technologies for more sustainable food production, reducing CO_2 emissions and the risk of accidents. As a result, sustainable business models in the agri-food sector require government efforts to support a cultural shift away from an individualistic and restricted logic of innovation toward one that is collectivistic, community-focused, and open-minded.

3.5.3 Research limitations

Although great care has been taken to ensure the validity and results of the study process, some limitations of the employed review process need to be identified, offering additional insights for improvement. Firstly, given the need to retrieve structured metadata for our investigation, we have included only documents published in the WoS database during the initial search, excluding additional databases such as Scopus, Google Scholar, and Business Source Complete. Therefore, future studies may integrate other database results into those offered by this paper. In addition, future research could conduct different types of literature reviews, such as bibliometric (Dzikowski, 2018) and structured literature reviews (Massaro et al., 2016).

Furthermore, we only considered articles and reviews published in double-blind peer-reviewed journals and omitted other kinds of publications such as conference proceedings, reports, and book chapters. However, given the topic's emergent nature, additional relevant literature from less influential sources may offer interesting inputs for future investigation on the latest technological applications. For example, future research could use academic sources in conjunction with practitioners' ones, such as the European patent office dataset (Secinaro et al., 2021), examining both scientific papers and original validated patents to provide holistic insights on how digitalisation is affecting the agri-food industry.

Finally, we only conducted descriptive clustering analysis, but also other kinds of analysis can be performed, such as topic modelling. While we have few constraints, we contribute to the I4.0 and agri-food sustainability literature by providing those interested in focusing on these issues research opportunities. In particular, Table 2 offers a robust research agenda, discussing significant insights to be explored in future investigations. For example, researchers could develop multiple case studies to analyse the impact of I4.0 technologies and sustainable practices on FLW mitigation, as well as investigate technological factors and circular practices affecting foodstuffs' sustainable consumer behaviour by conducting surveys.

4. Unveiling the potential of Industry 4.0 technologies for the food industry

The agri-food value chain has to take urgent action to address the serious environmental, economic, and social issues of food waste (Ciccullo et al., 2021). According to recently released FAO data, 33% of all foods manufactured globally, corresponding to about 930 million tons, are lost or wasted somewhere along the FSC (Abbate et al., 2023c; Dora et al., 2021). This problem is exacerbated by the fact that, by the end of 2050, the world's population is predicted to reach more than 9 billion, necessitating a 70% increase in global food production to ensure food security (Anastasiadis et al., 2022). To achieve this aim, as highlighted in the previous Chapter, food industry firms have started to adopt different digital technologies, increasing agricultural production and using fewer resources, thus reducing the environmental impact of production processes. Using I4.0 technologies, it is possible to achieve crucial farming goals (Lezoche et al., 2020), such as water-saving (O' Connor and Mehta, 2016), soil conservation (Li et al., 2002), GHG emissions reduction (Ochoa et al., 2014), and increase in crop yields (Mayer et al., 2015). Based on the above premises, together with the previous one, this Chapter aims to answer RQ1 (i.e. *How is digital transformation affecting the agri-food sector?*) by applying bibliometric analysis to 660 papers on I4.0 and food sustainability published over the last 27 years. Therefore, in order to overcome the drawbacks of the two methodologies employed independently, we adopted and integrated both systematic and bibliometric analysis in order to conduct an extensive evaluation of the literature on the subject, highlighting the knowledge structure, systematising the field's emerging streams, and gaps, suggesting potential future areas for agri-food sustainability research in relation to the fourth industrial revolution. The use of more than one method allowed us to provide a deeper understanding of the phenomenon under investigation; each method revealed a unique perspective, contributing to a more complete understanding of the subject under study. Notably, the bibliometric analysis results below show an overview of the top research-related scientific journals and papers in conjunction with the most productive and influential scholars, institutions, and countries. Moreover, both keywords co-occurrence analysis and cited references co-citation analysis highlight the main research clusters and the related sub-themes, providing meaningful discussions and overviews regarding key areas for future investigation. The nine-cluster classification enables policymakers and industry experts to assess the current I4.0 status of food technology and its effects on environmental sustainability and define the most relevant requirements for making appropriate choices about using current technologies for sustainability.

4.1 Methodology

4.1.1 Methods

Bibliometric analysis is a methodology broadly adopted in different knowledge branches due to its flexibility and aptitude for managing huge datasets (Fahimnia et al., 2015; Shashi et al., 2020b). It is a quantitative approach to highlighting, evaluating, and monitoring past studies (Garfield et al., 1964; Small, 1973; Dzikowski, 2018), thus providing a comprehensive overview of current scientific achievements (Gajdzik et al., 2020). The primary bibliometric approaches are performance analysis and science mapping (Dzikowski, 2018). The first provides an organised overview of the most productive researchers, leading papers and journals, and the most prominent research institutions and countries publishing in the research field (Merigó et al., 2016; Gaviria-Marin et al., 2019; Shashi et al., 2020c). In contrast, the second approach is a robust bibliometric method used to investigate the research field structure, identifying the relationship between different items (e.g., authors, articles, or keywords) (Morris et al., 2008; Kipper et al., 2020).

Therefore, by performing bibliometric analysis, researchers can generate a methodical, precise, and reproducible review procedure (Cao and Alon, 2020).

4.1.2 Material collection and selection phase

Articles were retrieved from the ISI Web of Science (WoS) database, which is considered a dependable scientific data source (van Leeuwen, 2006; Corallo et al., 2020). Compared to other academic research databases (e.g., Scopus and Google Scholar), WoS is considered a leading data source for the quality of journals indexed (Shashi et al., 2020b). Further, numerous bibliometric papers adopt WoS because it offers a set of metadata that is fundamental for this kind of investigation (Carvalho et al., 2013; Gaviria-Marin et al., 2019; Shashi et al., 2020c). The keywords used to retrieve the documents for our review were defined after a brainstorming process among researchers (also based on previous literature reviews on related topics) and refined after examining the frequency of the keywords used by earlier articles. Therefore, the following search query was used (searching documents that contain those words in the title, abstract, or keywords):

(("Industry 4.0" OR "industry4.0" OR "industrie 4.0" OR "industrie4.0" OR "industrial internet" OR "fourth industrial revolution" OR "4th industrial revolution" OR "industrial internet" OR "artificial intelligence" OR "cybersecurity" OR "cyber-security" OR "cyber security" OR "autonomous robot*" OR "cloud computing" OR "augmented reality" OR "virtual reality" OR "internet of things" OR "big data" OR "iot*" OR "additive manufacturing" OR "3d printing" OR "rapid manufacturing" OR "advanced manufacturing" OR "intelligent system*" OR simulation

OR "digital platform*" OR "machine learning" OR blockchain OR "block-chain" OR wearables OR "digital technolog*" OR "digital transformation" OR digitalization OR digitalisation OR "4.0" OR "digitization" OR "automation" OR "autonomous system" OR "robot" OR "cyber-physical" OR "phygital" OR "wearable" OR "sensor") AND ("environmental management" OR "sustainable operation*" OR "Environmental responsibility" OR "sustainable development" OR "triple bottom line" OR "circular economy" OR "environmental sustainability" OR "social sustainability" OR "corporate social responsibility") AND ("food" OR "agri-food" OR "agrifood" OR "agriculture")).

An initial sample of 890 documents was retrieved on 7th October 2021, without limiting the time range analysed. We refined our research by only collecting English-language publications. In addition, in order to further guarantee the quality of the sources examined, we limited our selection to articles and reviews published in peer-reviewed journals (Shashi et al., 2020c). As a result, the final sample comprises 660 relevant papers.

4.2 Performance assessment

606 articles and 54 literature reviews included in the final sample were published from 1994 to 2021. Table 3 reports the summary of the characteristics of the final sample.

Table 3. Overall results

Criteria	Number
Documents	660
Authors	2,903
Journals	328
Countries	85
Institutions	1206
Cited references	25,503

4.2.1 Distribution of papers by year of publication

The first two publications date back to 1994. Since the 90s, some concepts related to I4.0 technologies and sustainability have appeared, such as "simulation models" and "sustainable development", even if at the time a real concept of I4.0 has not been yet developed. In fact, the I4.0 concept firstly appeared in 2011 in a report diffused by the German government. Furthermore, I4.0 and sustainability concepts have gained significant attention in the scientific literature some years later. Starting from 2015, the published papers' trend increased exponentially until it attained the maximum of 206 publications in 2021. Figure 6 shows the papers' distribution over time, and the corresponding number of citations received in WoS. This analysis shows that the field of I4.0 and sustainability in the food sector has gained significant concern in the last five years. Between 2017 and 2021, about 76% of the papers examined have been published.

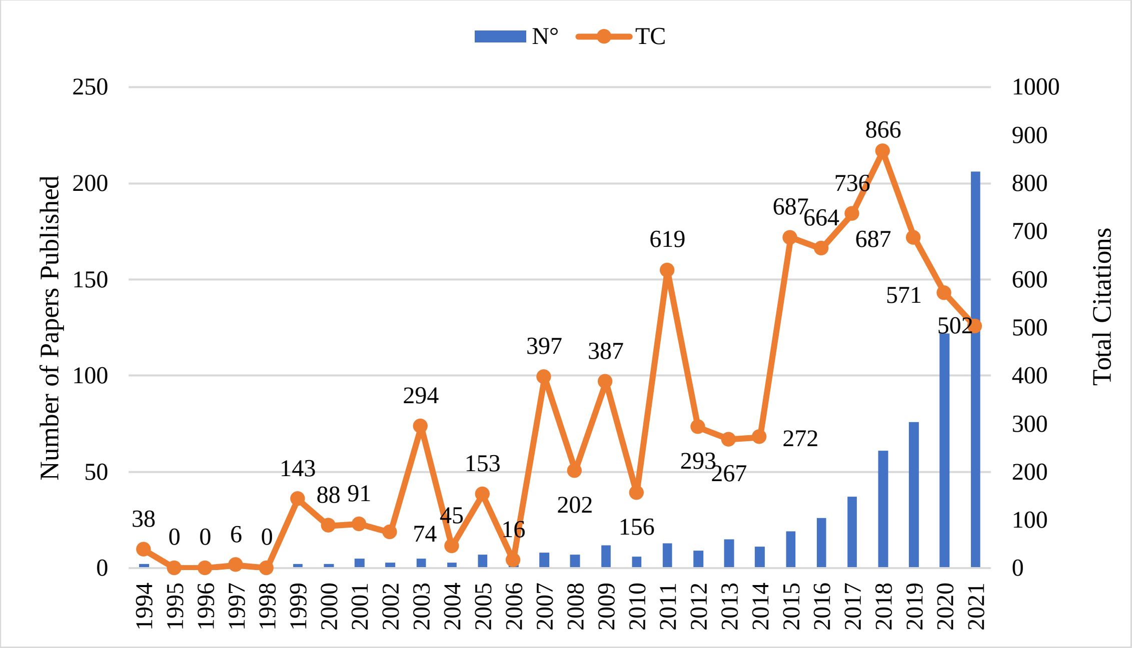


Figure 6. Distribution of papers and related citations over time

4.2.2 Top Documents

This analysis reveals the top documents which received the highest number of citations. Table 4 reports documents with at least 100 total citations (TC). The article *Modeling urban land-use change by the integration of cellular automaton and Markov model* published in 2011 by Guan et al. (2011) appeared as the article with the highest number of total citations received (278 citations), followed by *Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm* published in 2016 by Nobre and colleagues (270 citations) and *Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm* published in 2017 by Van Vuuren and colleagues (263 citations).

Hence, from this analysis emerges the commitment of the new technological paradigm (i.e. I4.0) in reaching sustainable development goals in the food industry, therefore reducing the environmental impact, and boosting agriculture and the quality of life through monitoring, modelling, and optimising operations.

Table 4. Documents regarding Industry 4.0 and sustainability in the food sector with at least 100 citations

Rank	Document	Journal	Reference	WoS TC
1	Modeling urban land use change by the integration of cellular automaton and Markov model	Ecological Modelling	Guan et al. (2011)	278
2	Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm	PNAS	Nobre et al. (2016)	270
3	Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm	Global Environmental Change	Van Vuuren et al. (2017)	263
4	Long-term experiments for sustainable nutrient management in China. A review	Agronomy for Sustainable Development	Miao et al. (2011)	258
5	Environmental parameters monitoring in precision agriculture using wireless sensor networks	Journal of Cleaner Production	Srbinovska et al. (2015)	217
6	From leaf to whole-plant water use efficiency (WUE) in complex canopies: Limitations of leaf WUE as a selection target	The Crop Journal	Medrano et al. (2015)	219
7	Rural sustainability under threat in Zimbabwe - Simulation of future land use/cover changes in the Bindura district based on the Markov-cellular automata model	Applied Geography	Kamusoco et al. (2009)	209
8	Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century	Global Environmental Change	Kriegler et al. (2017)	203
9	Evaluating taboo trade-offs in ecosystems services and human well-being	PNAS	Daw et al. (2015)	193
10	Methods and approaches to modelling the Anthropocene	Global Environmental Change	Verburg et al. (2016)	165
11	Global and regional health effects of future food production under climate change: a modelling study	The Lancet	Springmann et al. (2016)	163
12	Integrative modelling approaches for analysis of impact of multifunctional agriculture: A review for France, Germany and The Netherlands	Agriculture, Ecosystems & Environment	Rossing et al. (2005	111
13	Modelling multiple objectives of land use for sustainable development	Agricultural Systems	Zander et al. (1999)	110
14	Evaluating nitrogen taxation scenarios using the dynamic whole farm simulation model FASSET	Agricultural Systems	Berntsen et al. (2003)	109

4.2.3 Top journals

Due to I4.0 and sustainability's interdisciplinary nature, the 660 articles retrieved were published in 328 different journals. This study identifies the top 21 journals that published the highest number of papers or received the highest number of citations in the research field. The results are displayed in Table 5. This table reports the classification of the top 21 journals considering total publications (TP), total citations received (TC), as well as total citations received per publication (TC/TP).

Journal of Cleaner Production appeared as the leading journal in terms of total papers published (48 papers), followed by *Sustainability* (37 papers), and *Science of the total environment* (24 papers).

Global Environmental Change-Human and Policy Dimensions appeared as the top journal regarding total citations received (424 citations), followed by *Journal of Cleaner Production* (378), and *Agricultural Systems* (362 citations).

Furthermore, *Crop Journal* reached the highest number of total citations received per publication (164), followed by *Lancet* (106), and *Forestry Chronicle* (97).

These journals are very different in terms of the disciplines and objectives covered. As a result, this analysis shows that food sustainability and I4.0 topics have wider scopes, belong to different domains, and are covered by various journal outlets.

Table 5. Top 21 journals regarding Industry 4.0 and sustainability in the food sector

PART 1 (TP)			**PART 2 (TC)**		**PART 3 (TC/TP)**	
Rank	**Journal**	**TP**	**Journal**	**TC**	**Journal**	**TC/TP**
1	JOURNAL OF CLEANER PRODUCTION	**48**	GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	**424**	CROP JOURNAL	**164**
2	SUSTAINABILITY	**37**	JOURNAL OF CLEANER PRODUCTION	**378**	LANCET	**106**
3	SCIENCE OF THE TOTAL ENVIRONMENT	**24**	AGRICULTURAL SYSTEMS	**362**	FORESTRY CHRONICLE	**97**
4	REMOTE SENSING	**15**	AGRONOMY FOR SUSTAINABLE DEVELOPMENT	**335**	APPLIED GEOGRAPHY	**87**
5	AGRICULTURAL SYSTEMS	**12**	ECOLOGICAL MODELLING	**280**	GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	**84.8**
6	JOURNAL OF ENVIRONMENTAL MANAGEMENT	**10**	AGRICULTURE ECOSYSTEMS & ENVIRONMENT	**236**	INTERNATIONAL JOURNAL OF LIFE CYCLE ASSESSMENT	**69**
7	AGRICULTURAL WATER MANAGEMENT	**8**	SCIENCE OF THE TOTAL ENVIRONMENT	**190**	AGRONOMY FOR SUSTAINABLE DEVELOPMENT	**67**
8	BRITISH FOOD JOURNAL	**8**	APPLIED GEOGRAPHY	**174**	CURRENT SCIENCE	**60**
9	LAND USE POLICY	**8**	CROP JOURNAL	**164**	AGRICULTURE ECOSYSTEMS & ENVIRONMENT	**59**
10	WATER	**8**	AGRICULTURAL WATER MANAGEMENT	**160**	IEEE TRANSACTIONS ON SYSTEMS MAN AND CYBERNETICS PART C-APPLICATIONS AND REVIEWS	**53**
11	APPLIED ENERGY	**7**	APPLIED ENERGY	**145**	LANDSCAPE AND URBAN PLANNING	**49**
12	AGRONOMY-BASEL	**7**	ECOLOGICAL ECONOMICS	**119**	PLANT PRODUCTION SCIENCE	**49**
13	ECOLOGICAL MODELLING	**6**	LANCET	**106**	CLIMATE CHANGE AND FOOD SECURITY IN SOUTH ASIA	**47**
14	SENSORS	**6**	IEEE TRANSACTIONS ON SYSTEMS MAN AND CYBERNETICS PART C-APPLICATIONS AND REVIEWS	**106**	JOURNAL OF MANUFACTURING SYSTEMS	**47**
15	INTERNATIONAL JOURNAL OF ENVIRONMENTAL RESEARCH AND PUBLIC HEALTH	**6**	BRITISH FOOD JOURNAL	**106**	ECOLOGICAL MODELLING	**46.66**
16	GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS	**5**	SUSTAINABILITY	**105**	SCIENTIA HORTICULTURAE	**46**
17	AGRONOMY FOR SUSTAINABLE DEVELOPMENT	**5**	ECOLOGY AND SOCIETY	**98**	ENVIRONMENTS	**45**
18	FIELD CROPS RESEARCH	**5**	FORESTRY CHRONICLE	**97**	INDUSTRIAL MARKETING MANAGEMENT	**43**
19	SUSTAINABLE PRODUCTION AND CONSUMPTION	**5**	JOURNAL OF ENVIRONMENTAL MANAGEMENT	**95**	FUTURE INTERNET	**43**
20	COMPUTERS AND ELECTRONICS IN AGRICULTURE	**5**	FIELD CROPS RESEARCH	**85**	GLOBAL ECOLOGY AND BIOGEOGRAPHY	**42**

PART 1 (TP)			**PART 2 (TC)**		**PART 3 (TC/TP)**	
Rank	**Journal**	**TP**	**Journal**	**TC**	**Journal**	**TC/TP**
21	ENVIRONMENTAL EARTH SCIENCES	**5**	SUSTAINABLE PRODUCTION AND CONSUMPTION	**76**	AGRICULTURAL AND FOREST METEOROLOGY	**35**

4.2.4 Country analysis

This analysis reveals the most productive and influential countries. The sample of 660 publications comprises authors working in 85 countries, and 25.8% of these countries published only one paper. Table 6 (Part 1) displays the 10 most productive countries regarding total publications (TP), whereas Table 6 (Part 2) shows the 10 most influential countries concerning total citations received (TC). The distribution of documents by geographic area is also reported in Figure 7. Notably, some papers were co-authored by researchers of different nationalities; in this case, the country of each researcher that co-authored the article is counted. While if researchers from the same country co-authored a paper, their country is counted once even if two or more researchers co-authored the manuscript (Shashi et al., 2020a). As shown in Figure 7, both China and the USA are two leading countries in the I4.0 and food sustainability research, with 110 and 75 papers published respectively, followed by Italy with 52 papers. It is not surprising because, even if the I4.0 was raised in Europe, in 2015 the Chinese economy launched the "Made in China 2025", which is an initiative to convert China into a world-leading industrial power, therefore drawing straight encouragement from Germany's "Industry 4.0" strategy (Wang et al., 2020). Similarly, the USA developed a project called “A Strategy for American Innovation” to create new jobs and strengthen the country's leadership in the information and communication technology sector (Min et al., 2018). Nevertheless, Europe is at the top of the ranking concerning publication on I4.0 and sustainability in the food sector since about 45% of the top publishing countries' papers are European (Table 6, Part 1). Concerning the citations, the USA is the most influential country with 1,831 citations received, followed by China (1,354 citations) and Germany (984 citations). In this second case, the highest citations received (about 40%) belong again to the European countries (Table 6, Part 2).

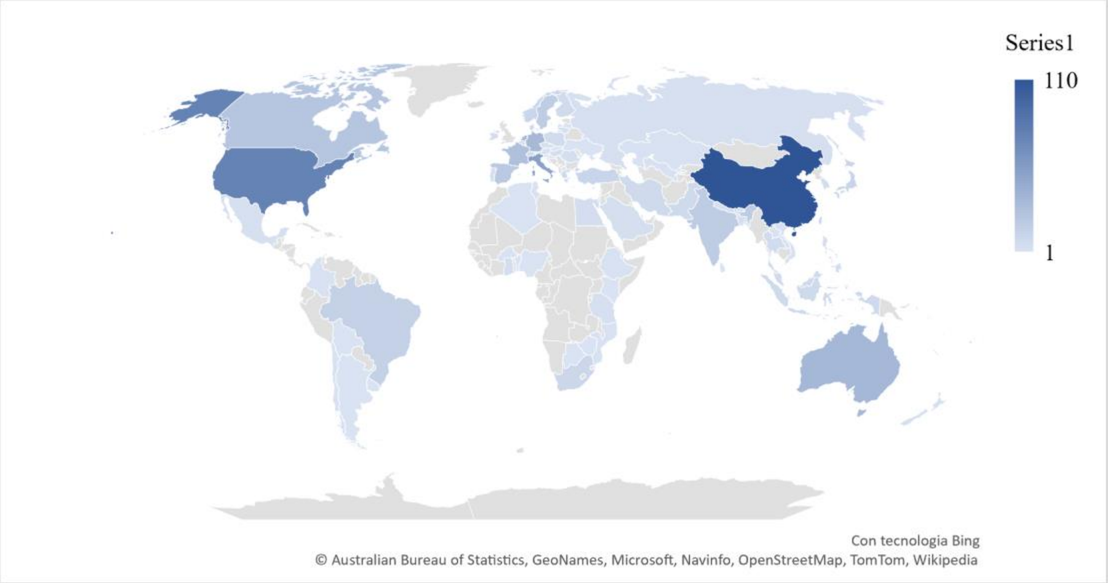


Figure 7. Documents' distribution by geographical area

Table 6. Top 10 countries based on total number of papers published (Part1) and total number of citations received (Part 2)

Part 1 (TP)				**Part 2 (TC)**			
Rank	**Country**	**TP**	**TC/TP**	**Rank**	**Country**	**TC**	**TC/TP**
1	China	110	12.31	1	USA	1831	24.41
2	USA	75	24.41	2	China	1354	12.31
3	Italy	52	11.23	3	Germany	984	29.82
4	England	35	19.94	4	Australia	749	22.03
5	Australia	34	22.03	5	England	698	19.94
6	Germany	33	29.82	6	Japan	649	54.08
7	Netherlands	32	20.28	7	Netherlands	649	20.28
8	France	27	18.11	8	Italy	584	11.23
9	Canada	23	20.91	9	France	489	18.11
10	Spain	21	14.62	10	Canada	481	20.91

4.2.5 Most productive authors

This analysis reveals that 2,903 researchers have contributed to the writing of 660 papers. On average, each article was authored by four researchers. Yet, 97.2% of the authors have contributed to the publication of just one document, implying that I4.0 and food sustainability is mainly a research field of diversification instead of specialisation (Ertz and Leblanc-Proulx, 2018; Shashi et al., 2020c). To evade biases associated with researchers' shortened or full names (e.g., “Bonfante, Antonello” and

“Bonfante, A.”, emerging as two diverse academicians, although they represent the same author) we manually checked and revised the spelling of all papers' authors.

Therefore, the most productive researchers are identified and sorted considering the total number of publications (TP). Specifically, Table 7 reports the researchers who published a minimum of two articles in the field and their affiliation. For an equal number of papers published, the author's ranking is obtained considering the total number of citations (TC). From China, Yuxin Miao is the highest contributor with 5 papers published, followed by Antonello Bonfante with 4 papers (from Italy), and Fusuo Zhang with 3 papers (from China). In the fourth and fifth positions there are two authors, Andrzej Tabeau and Hans Van meijl, who co-authored 2 articles published on the topic and belong to the Wageningen University, the most influential institution on the subject investigated, as discussed in the following sub-section.

Table 7. The 6 most productive authors

	Author	**Affiliation**	**TP**	**TC**	**TC/TP**
1	Miao, Yuxin	China Agricultural University, Coll Food Sci & Nutr Engn, Beijing, Peoples R China	5	285	57
2	Bonfante, Antonello	Consiglio Nazionale delle Ricerche, Inst Mediterranean Agr & Forest Syst CNR ISAFOM, Ercolano, Italy	4	18	4,5
3	Zhang, Fusuo	China Agricultural University, Beijing Key Lab Farmland Soil Pollut Prevent & Re, Beijing, Peoples R China	3	283	94,33
4	Tabeau, Andrzej	Wageningen University & Research, Wageningen Econ Res, The Hague, Netherlands	2	158	79
5	Van meijl, Hans	Wageningen Econ Res, Agr Econ & Rural Policy Grp, The Hague, Netherlands	2	158	79
6	Verburg, Peter H.	Vrije University Amsterdam, Environm Geog Grp, Amsterdam, Netherlands	2	134	67

4.2.6 Top research organisations

This analysis shows that 1206 research organisations have published on I4.0 and sustainability in the food industry from 1994 to 2021. Further, 84.19% of these institutions have published only one article, suggesting that few research organisations focus on this field. Moreover, we manually checked all papers' organisations names to manage their different spelling (e.g., “Wageningen uni & res” and “uni Wageningen & res”, which appear as two diverse universities). The leading 20 organisations in terms of total publications are reported in Table 8 - Part 1, while the rank based on total citations received by each institution is reported in Table 8 – Part 2. Founded on the total papers published (Table 8 – Part 1), Chinese Academy of Science (30 articles), Wageningen University & Research (16 articles), Beijing Normal University (13 articles), China Agricultural University (12 articles), and

Texas A&M University (8 articles) appeared as the top 5 most prominent research organisations. Instead, based on the number of citations received (Table 8 – Part 2), the Wageningen University & Research (402 citations), Chinese Academy of Science (398 citations), China Agricultural University (384 citations), Beijing Normal University (314 citations), and Texas A&M University (305 citations) emerged as the top 5 most influential research organisations. Further, the results are consistent with the country analysis' findings since these leading organisations are included in the most prolific and influential countries.

Table 8. Top 20 institutions based on total publications (Part 1) and total citations received (Part 2)

Part 1 (TP)					**Part 2 (TC)**				
Rank	**Organization**	**Country**	**TP**	**TC/TP**	**Rank**	**Organization**	**Country**	**TC**	**TC/TP**
1	Chinese Academy of Science	China	30	13.27	1	Wageningen University & Research	Netherlands	402	25.13
2	Wageningen University & Research	Netherlands	16	25.13	2	Chinese Academy of Science	China	398	13.27
3	Beijing Normal University	China	13	24.15	3	China Agricultural University	China	384	32.00
4	China Agricultural University	China	12	32.00	4	Beijing Normal University	China	314	24.15
5	Texas A&M University	United States	8	38.13	5	Texas A&M University	United States	305	38.13
6	National Taiwan University	Taiwan	7	12.00	6	Stockholm university	Sweden	281	70.25
7	Wuhan University	China	7	6.86	7	Chongqing Jiaotong University	China	198	198.00
8	University of Montpellier	France	6	8.17	8	Chongqing Normal University	China	198	198.00
9	University of Rome Sapienza	Italy	6	3.17	9	Chongqing University	China	198	198.00
10	University of British Columbia	Canada	5	34.80	10	Guizhou Academy of Science	China	198	198.00
11	Humboldt-University of Berlin	Germany	5	33.80	11	Saga University Honjo Campus	Japan	298	198.00
12	Nanjing Agricultural University	China	5	19.80	12	University of Central Florida	United States	178	59.33
13	University of Minnesota	Unites States	5	16.80	13	University of British Columbia	Canada	174	34.80
14	European Commission	-	5	7.00	14	Bindura University of Science Education	South Africa	170	170.00
15	University of Naples Federico II	Italy	5	5.40	15	University of Tsukuba	Japan	170	170.00
16	Stockholm university	Sweden	4	70.25	16	Saints Cyril and Methodius University	North Macedonia	169	169.00
17	Vrije University Amsterdam	Netherlands	4	40.75	17	Humboldt-University of Berlin	Germany	169	33.80
18	Leibniz Centre for Agricultural Landscape Research	Germany	4	28.75	18	Catholic University of Leuven	Belgium	164	164.00
19	Queensland University of Technology	Australia	4	9.25	19	University of the Balearic Islands	Spain	164	164.00
20	National Institute of Agronomic Research	France	4	7.25	20	Vrije University Amsterdam	Netherlands	163	40.75

4.3 Science mapping analysis

This analysis shows the research domain dynamic structures (Merigò et al., 2017; Gaviria-Marin et al., 2019), and it can be implemented through numerous computer software. In this study, we used VOSviewer software to carry out network analysis. VOSviewer is a user-friendly tool broadly used to elaborate and visualise bibliometric networks (van Eck and Waltman, 2010; Shashi et al., 2020c) and based on the visualisation of similarities (VOS) algorithm, which considers similarities between objects (Ertz and Leblanc-Proulx, 2018).

VOSviewer generates a bibliometric network containing nodes and links. The nodes represent the network analysis unit and could be characterised by documents, authors, journals, keywords, or institutions (Rizzi et al., 2014; Shashi et al., 2020c). The size of the nodes and labels suggests the frequency of occurrence. The higher the node and label dimension, the higher the frequency of occurrence. The relationship between nodes exists if links connect them. The wider the link is, the greater the relationship between the items (e.g., greater co-occurrence of keywords). Each link also has a specific strength, which is proportional to the relationship between nodes. The greater the link strength, the stronger the relationship between nodes (e.g., stronger co-citation of articles). Moreover, the distance between two nodes indicates the relatedness between them. A shorter length mainly reveals a more substantial relationship; the higher the distance between two nodes, the lower their relationship. As a result, the relationship between nodes is measured through the link's thickness, the distance between the items, and the link strength. Finally, the nodes with the same colour belong to the same cluster. The nodes in the same cluster uncover their analogy and similar features (Shashi et al., 2020c). In this study, VOSviewer was used to analyse the co-occurrence of keywords as well as the co-citation of cited references, which will be discussed in detail in two following sub-sections.

4.3.1 Co-occurrence analysis of keywords

Keywords co-occurrence is recognised as a great method for identifying research themes since it allows for analysing the content of the papers and evaluating the co-occurrence relationship between notions (Shashi et al., 2020a). To account for different variants of some terms (e.g., “system” and “systems”, “big-data analytics” and “big data analytics”, which emerge as diverse keywords, although they indicate the same concept), we manually checked all the papers' keywords. This analysis identified 3,036 different keywords in the sample of 660 articles. Only keywords with at least nine repetitions were included in the investigation. Thus, an amount of 124 keywords were shortlisted, and Figure 8 presents its network visualisation. VOSviewer divided the keywords of I4.0 and food sustainability into four clusters.

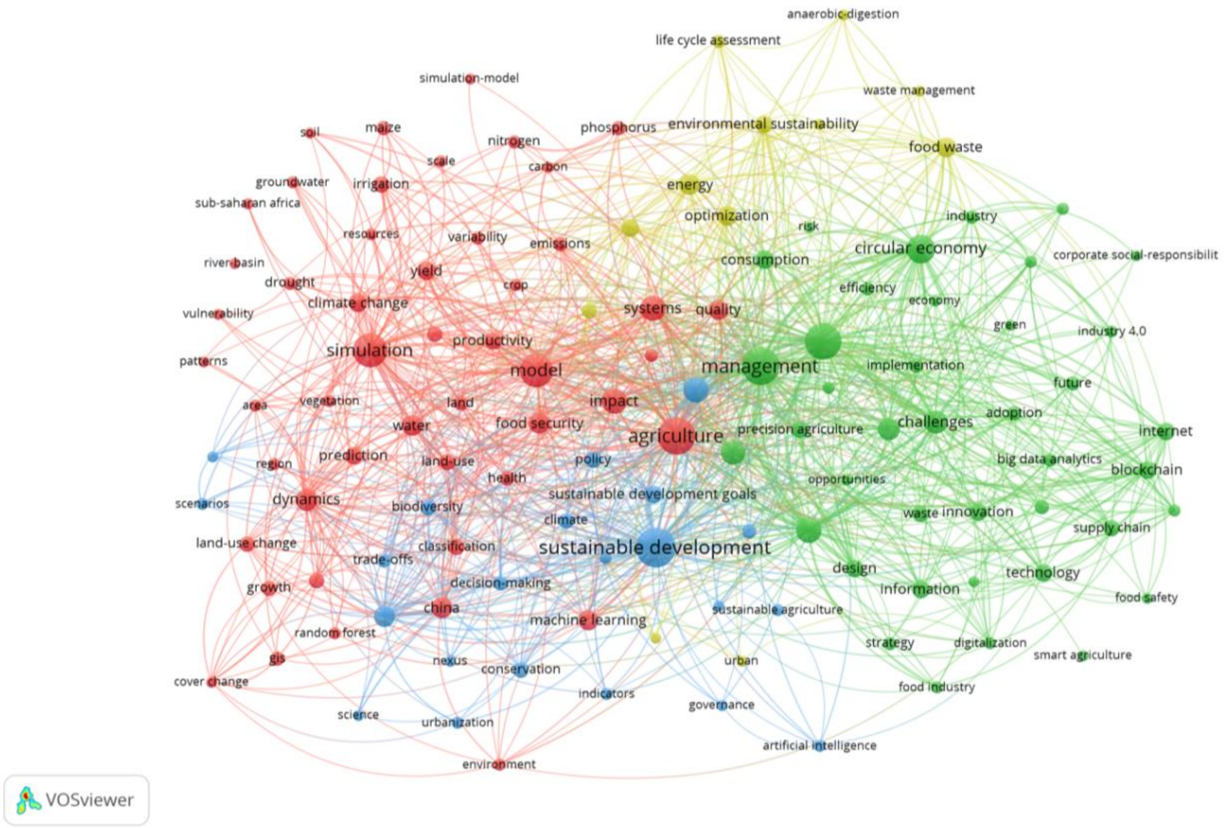


Figure 8. Co-occurrence network of keywords

For example, machine learning tools have been adopted to detect events of foodborne diseases from social media (Effland et al., 2018; Tao et al., 2020) and provide dietary advice (Amato et al., 2021). Besides, information technology dissemination has allowed the collection of a large volume of data. Therefore, big data analytics methods have been applied to carry out predictive intuitions about farm procedures (e.g., crop yield predictions) (Tao et al., 2020). Other recent keywords, such as “greenhouse gas emissions”, “life cycle assessment”, and “circular economy”, demonstrate the food industry transition trend from a linear to a CE model, saving material costs and reducing the environmental implications of food production (Ingrao et al., 2018). Notably, the CE in the food context involves reducing the food waste generated, recycling food by-products and waste, and ecological nutrition (Jurgilevich et al., 2016), reducing the environmental implications of the FSC (Tseng et al., 2019). Notably, I4.0 technologies have the potential to support the CE transition, reducing waste and CO_2 emissions, encouraging remanufacturing, improving the efficiency of essential resources like water, electricity, and gas, and upgrading business models and corporate missions (Massaro et al., 2021).

4.3.2 Co-citation analysis of cited references

Cited references co-citation analysis enables the researcher to uncover the structure of the research field by analysing papers frequently cited simultaneously (Gaviria-Marin et al., 2019). More specifically, two documents establish a co-citation relationship when they are cited together by a third article (Boyack et al., 2010; Liao et al., 2018). The higher the frequency that two papers are cited together, the higher the co-citation strength (Small, 1973; Shashi et al., 2020c). Moreover, high (low) co-citations reveal common (uncommon) research topics among papers (Benckendorff and Zehrer, 2013; Shashi et al., 2020c). Therefore, this analysis detects clusters of themes and examines how they are linked (Chen, 2006; Shashi et al., 2020c). In the primary sample of 660 papers, a total amount of 32,970 cited references were found. However, considering articles with at least 3 citations, 255 papers cited 954 times were found, and nine clusters have been identified. Notably, Table 9 highlights the research clusters and the related references, while Figure 9 shows its network visualisation.

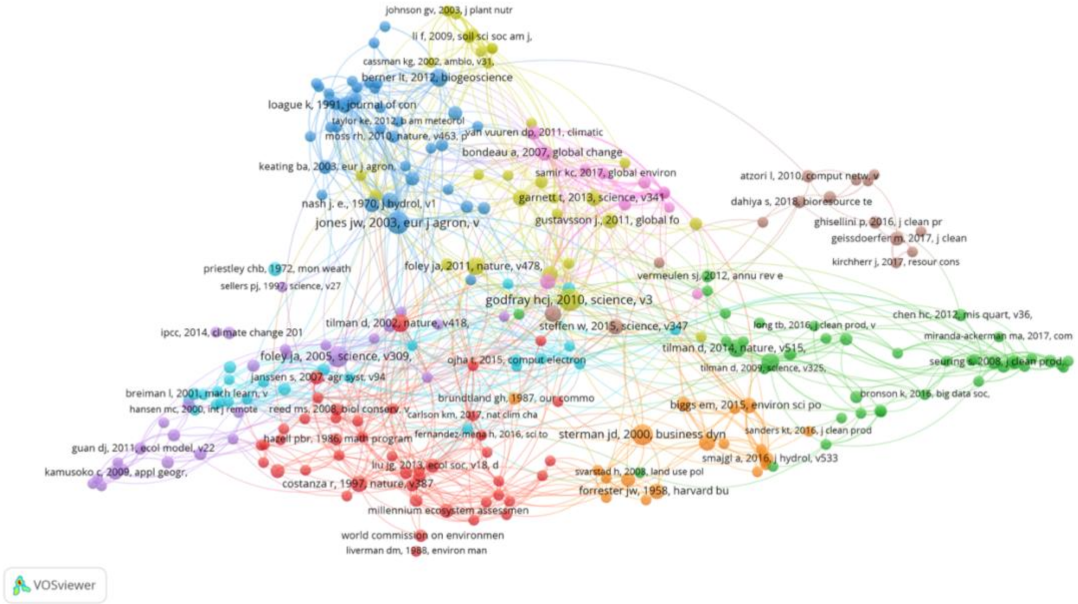


Figure 9. Co-citation network of cited references

Analysing the articles that belong to the same cluster makes it possible to understand the related research area, since documents frequently cited simultaneously most probably belong to the same research domain (Hjørland, 2013). Hence, the content of each cluster's papers was carefully analysed to detect the main research topic.

Cl*uster 1 (red) - ecosystem management (EM).* This cluster analyses theoretical knowledge and different approaches for modelling ecosystems. Costanza et al. (2017) provided an overview of the ecosystem service (ES) debate, focusing on institutions, policies, on-the-ground actions, and controversies. Bennett et al. (2009) reviewed the literature on ES and proposed relationships between services based on drivers' roles and interactions. Raudsepp-Hearne et al. (2010) designed a framework for analysing the supplying of different ES across landscapes. Daw et al. (2011) identified the main problems concerning coastal ES in developing countries. Biggs et al. (2012) summarised diverse policy-relevant principles for improving ES resilience. By contrast, Altieri et al. (1999) described various agroecosystem management practices that enhance functional biodiversity. Finally, Costanza et al. (1997) evaluated the economic value of 17 ES for 18 biomes based on scientific articles and original calculations.

Cluster 2 (green) – Supply Chain Management (SCM). This cluster evaluates potential linkages between green SCM practices/technologies and economic, environmental, and social performance. Over the past ten decade, academics and business professionals have become increasingly aware of the need to promote sustainability practices inside supply chains (Metta and Badurdeen, 2012). Different conceptual frameworks were proposed. For instance, Seuring et al. (2008) designed a theoretical framework to summarise SCM research. The framework developed by Carter et al. (2008) investigates sustainable SCM, demonstrating the relationships between economic, environmental, and social outcomes. Further with this regard, Rao et al. (2005) identified possible linkages between green SCM, economic performance and competitiveness, while Eltayeb et al. (2011) conducted a survey to evaluate the impact of green SCM initiatives on financial and environmental performance. Moreover, Govindan et al. (2013) used the fuzzy multi-criterion method to select suppliers correctly, based on the triple bottom line (TBL) framework. Other scholars focused on new digital technologies applied to improve sustainability in the food sector. Wognum et al. (2011) explored the new information and communication technologies to strengthen FSC sustainability and improve relations with stakeholders, while Turken et al. (2020) reviewed different CE practices that significantly impact the FSC. Regarding big data, some scholars reviewed the literature and showed that the current practice of big data analytics is leading to essential transformations in the interactions among the FSC networks' players (Wolfert et al., 2017), further solving different relevant problems in agriculture (Kamilaris et al., 2017). These technologies promise increased food production with fewer resources and a reduced ecological footprint (Weersink et al., 2018).

Other studies focused on the optimisation and planning tools to support SCM and the principal methodologies to evaluate the product's carbon footprint. Akkerman et al. (2010) tested approaches to quantitative operations management for food distribution. Ahumada et al. (2009) reviewed the main planning models that have been successfully implemented in the FSC, classifying the models according to particular features (e.g., the optimisation approaches used, and the type of crops modelled). Other contributions focused on the LCA approach, a holistic technique extensively used in this industry to evaluate the product's environmental impact during all the supply chain phases (de

Vries et al., 2010). In this regard, in conjunction with Data Envelopment Analysis (DEA), Egilmez et al. (2014) proposed the Economic Input-Output Life Cycle Assessment (EIO-LCA) model to assess the direct and indirect environmental implications of 33 U.S. food manufacturing sectors and to benchmark their sustainability efficiency. Finally, Notarnicola et al. (2017) proposed the LCA approach to assess food consumption's environmental impact, using a basket of food products as representative of the average food and beverage consumption in Europe.

Cluster 3 (blue) – simulation models for environmental management. This cluster contains studies concerning mainly crop and water modelling techniques, developed as decision-support tools. In this regard, Arnold et al. (1998) described the Soil and Water Assessment Tool (SWAT), developed to evaluate the influence of environment and management on water use, nonpoint source loadings, and contamination of pesticides. Further with regards to water modelling prediction, Loague et al. (1991) developed a mathematical model to forecast pollutants' mobility and persistence towards and within groundwater systems. Moreover, to simulate soil moisture and salinity concentration, Ren et al. (2016) used the HYDRUS-1D model, while Steduto et al. (2009) introduced the AquaCrop model that simulates crop yields in rainfed, supplementary, deficit and maximum irrigation conditions as a function of water consumption. Regarding the agricultural systems, Jones et al. (2003) analysed the new Agrotechnology Transfer Decision Support System (DSSAT-CSM), built to model soil, crop, weather, and management. Other researchers described the Agricultural Production Systems Simulator (APSIM); it was used to model the biophysical processes inherent to agricultural systems (McCown et al., 1996; Keating et al., 2003; Chen et al., 2010). Finally, Cabelguenne et al. (1999) presented the Erosion Productivity Impact Calculator (EPIC) model, which was updated to simulate the effects on biomass production and grain yield of water and nitrogen stress.

Cluster 4 (yellow) - food production and food security. The main problems and difficulties associated with securing sufficient food production to fulfil the estimated rise in food demand in the upcoming years are the focus of this cluster. In this regard, Tilman et al. (2011) predicted global crop production demand in 2050, assessing the environmental effects of alternative forms of meeting such demand. Hence, some scholars focused on the theme of sustainable agriculture intensification, which has been highlighted as a green alternative to boosting crop yields rather than clearing more land for agri-food production (Ray et al., 2013). In this respect, Foley et al. (2011) simultaneously examined various techniques for boosting crop yields and reducing agriculture's environmental footprint. A multifaceted and related global strategy to enhance food security was analysed by Godfray et al. (2010), while recent patterns and potential trajectories in crop yields, usage of land and N fertilisers, carbon sequestration, and emissions of greenhouse gases were evaluated by Cassman et al. (2003). Van Ittersum et al. (2013) examined numerous methods for estimating yield gaps, the knowledge of which is essential to direct the intensification of sustainable agriculture. In order to estimate the average yields based on current knowledge of crop ecophysiology and soil biogeochemistry owing to soil-crop system management techniques, Chen et al. (2014) conducted 153 site-year field trials.

Besides, other studies focused on the use of nitrogen (N). Wu et al. (2015) surveyed 6,611 small-scale rice farmers to establish an optimal approach to N management. Finally, a sensor-based precision N management approach was established by other researchers to boost N-use efficiency (NUE) and reduce environmental damage risks (Li et al., 2009; Yao et al., 2012).

Cluster 5 (purple) - *land-use changes*. The articles in this cluster deal with the science of land change, which aims to comprehend the dynamics of land cover/use as a hybrid human-environment framework to provide theories, guidelines, models, and practical applications pertaining to environmental and social issues (Turner II et al., 2007). In recent decades, the increase in global cultivated land and urban areas caused an increase in energy, water, and fertiliser consumption and biodiversity and forest resource losses, generating significant environmental impacts. Therefore, the task is to balance the trade-off between immediate human needs (e.g., more food and more housing) and preserve the ability of the biosphere to provide long-term goods and services (Foley et al., 2005). In this regard, Lambin et al. (2001) discussed the main antecedents and driving forces of land-cover changes. Other researchers developed spatially explicit probabilistic projections of global urban land-cover changes and examined risks for sustainability. By contrast, Wu et al. (2006) examined the land-use change dynamics by employing satellite remote sensing and geographic information systems (GIS). Other studies focused on land use and land cover change modelling. For instance, Kamusoco et al. (2009) and Guan et al. (2011) – also belonging to the top 14 documents – developed a Markov-Cellular Automata model to evaluate land use temporal change and spatial distribution. Further, Verburg et al. (2006) analysed different approaches to land use modelling to determine the risks and trade-offs of natural area security, while Deng et al. (2008) developed the Dynamics of Land Systems (DLS) to simulate different land system's dynamics. Finally, the Land Use Model Intercomparison Project (LUMIP) was examined by Lawrence et al. (2016), which seeks to investigate the environmental implications of land use and land cover transition.

Cluster 6 (*light blue) - emerging technologies in agriculture*. This cluster mainly concerns the applications of precision and smart agriculture technologies. For instance, Ojha et al. (2015) reviewed the scientific literature on wireless sensor network (WSN) for agri-food production, while Srbinovska et al. (2015) – also belonging to the top 14 documents – developed a WSN architecture for the vegetable greenhouse to reduce management costs and environmental impact. Other studies are focused on remote sensing technologies. To meet different knowledge needs, remote sensing science has developed increasingly accurate, consistent, and robust methods to capture land dynamics

(Olofsson et al., 2014). In this regard, Mulla (2013) explored the major applications of remote sensing in precision agriculture, such as soil organic matter sensors and satellite, aerial, handheld, or tractor-mounted sensors. Some researchers adopted Google Earth Engine (GEE), which is a cloud-based platform for mapping crop production (Dong et al., 2016; Gorelick et al., 2017). For instance, Dong et al. (2016) mapped a region in north-eastern Asia used for paddy rice farming. A paddy rice mapping technique was created by Xiao et al. (2005) that determines the first flooding cycle and transplants of paddy rice fields using a time series of three vegetation indicators generated from Moderate Resolution Imaging Spectroradiometer (MODIS) pictures. By contrast, Blaschke et al. (2014) investigated the potential of Geographic Object-based Image Analysis (GEOBIA), which is an approach for evaluating remote sensing imagery, while Hansen et al. (2013) used satellite data from Earth observation to chart global forest losses. Finally, Kussul et al. (2017) proposed an application of deep learning (DL) architecture employing multitemporal satellite images to grade crops and land cover.

Cluster 7 (orange) - Water-Energy-Food (WEF) Nexus. Papers included in this cluster are mainly aimed at developing theoretical frameworks to manage better the WEF Nexus (Bazilian et al., 2011; Rasul, 2016; Smajgl et al., 2016) or propose both qualitative and quantitative methods to analyse the Nexus (Endo et al., 2015). In response to environmental and social challenges, such as climate change, resource scarcity, and population growth, the WEF nexus has been gaining increasing attention in the scientific literature (Bai and Sarkis, 2019). Uen et al. (2018), for example, suggested a systemic three-fold scheme that synergistically optimises the WFE Nexus's advantages. In order to build an efficient agricultural drought management system, Zhang et al. (2018) proposed a WEF simulation and optimisation approach for real-time drought monitoring and irrigation management. Finally, Zhang et al. (2017) developed a multi-period socioeconomic model based on inputs reflecting production costs, socioeconomic demands, and environmental controls to predict how to fulfil WEF demand.

Cluster 8 (brown) - Circular Economy (CE). Papers belonging to this cluster mainly address CE definition, challenges, strategies, and tools. Kirchherr et al. (2017), Merli et al. (2018), Lieder et al. (2016) and Ghisellini et al. (2016) reviewed the literature to conceptualise the CE paradigm, focusing on definitions, fundamental concepts, CE features and outlooks, benefits and drawbacks, modelling instruments, and approaches, as well as on strategies to promote the CE implementation, such as the Material Flow Analysis and the LCA. Geissdoerfer et al. (2017) shed light on the similarities, disparities, and connections between CE and sustainability.

Other research focused on CE strategies meant to valorise food waste. Notably, several studies have shown that the exploitation of food waste as a potential feedstock in biological processes to create various biobased products, as well as green chemicals and fuels, could be a greener alternative compared to landfill (Lin et al., 2013; Arancon et al., 2013; Dahiya et al., 2018).

Cluster 9 (pink) - Shared Socio-Economic Pathways (SSPs). Papers belonging to this cluster concern the analysis of scenarios of projected socio-economic global changes. Using the SSPs framework, studies have mainly been focused on climate changes (e.g., Kriegler et al., 2012; O' Neill et al., 2014; Van Vuuren et al., 2014), land use (Popp et al., 2017), air pollution (Rao et al., 2017), energy usage (Bauer et al., 2017), population scenarios (Samir and Lutz, 2017), energy systems (Rogelj et al., 2015).

Table 9. Clustering resulting for the most cited references

Cluster 1: Ecosystem Management (152 citations)		**Cluster 2: Supply Chain Management (138 citations)**	
Tilman et al., 2002 (8) Costanza et al., 1997 (7) Janssen et al., 2007 (5) Liu et al., 2013 (5) Millennium ecosystem assessment, 2005 (5) Parker et al., 2003 (5) Costanza et al., 2017 (4) Grimm et al., 2005 (4) Hazell et al., 1986 (4) Raudsepp-hearne et al., 2010 (4) Reed et al., 2008 (4) World commission on environment and development, 1987 (4) Altieri et al., 1999 (3) Becu et al., 2003 (3) Biggs et al., 2012 (3) Borjeson et al., 2006 (3) Carlson et al., 2017 (3) Cash et al., 2003 (3) Daw et al., 2011 (3) Dewit et al., 1988 (3)	Erb et al., 2016 (3) Fernandez-mena et al., 2016 (3) Filatova et al., 2013 (3) Folke et al., 2005 (3) Groot et al., 2007 (3) Herrero et al., 2010 (3) Liu et al., 2007 (3) Liverman et al., 1988 (3) Magliocca et al., 2013 (3) Metzger et al., 2006 (3) Ostrom et al., 2009 (3) Ostrom et al., 1990 (3) Pacini et al., 2004 (3) Scherr et al., 2008 (3) Tscharntke et al., 2005 (3) United nations, 2015 (3) Van asselen, et al. 2013 (3) Van ittersum et al., 1998 (3) Van ittersum et al., 2008 (3) Veldkamp et al., 1996 (3) Verburg et al., 2016 (3) Voinov et al., 2010 (3) Zander et al., 1999 (3)	Tilman et al., 2014 (8) Wolfert et al., 2017 (8) Seuring et al., 2008, (5) Wognum et al., 2011 (5) Ahumada et al., 2009 (4) Chen et al., 2012 (4) Finnveden et al., 2009 (4) Kamilaris et al., 2017 (4) Rao et al., 2005 (4) Rose et al., 2018 (4) Vermeulen et al., 2012 (4) Akkerman et al., 2010 (3) Baron et al., 1986 (3) Bongiovanni et al., 2004 (3) Bronson et al., 2016 (3) Carter et al., 2008 (3) Cox et al., 2002 (3) De vries et al., 2010 (3) Egilmez et al., 2013 (3) Egilmez et al., 2014 (3)	Eltayeb et al., 2011 (3) Goovaerts et al., 1997 (3) Govindan et al., 2013 (3) Iso, 2006 (3) Long et al., 2016 (3) Maloni et al., 2006 (3) Miranda-ackerman et al., 2017 (3) Notarnicola et al., 2017 (3) Phalan et al., 2011 (3) Podsakoff et al., 2003 (3) Rogers et al., 2003 (3) Stehfest et al., 2009 (3) Svarstad et al., 2008 (3) Tilman et al., 2009 (3) United nations (3) Van der vorst et al., 2009 (3) Weersink et al., 2018 (3) Willett et al., 2019 (3) Zhu et al., 2008 (3)
Cluster 3: Simulation Models for Environmental Management (151 citations)		**Cluster 4: Food Production and Food Security (123 citations)**	
Jones et al., 2003 (13) Berner et al., 2012 (8) Loague et al., 1991 (6) Nash et al., 1970 (6) Olesen et al., 2002 (6) Keating et al., 2003 (5) Porter et al., 2014 (5) Steduto et al., 2009 (5) Arnold et al., 1998 (4) Krause et al., 2005 (4) Lambin et al., 2001 (4) Mccown et al., 1996 (4) Moss et al., 2010 (4)	Fang et al., 2010 (3) Feddes et al., 1978 (3) Geerts et al., 2009 (3) Holzworth et al., 2014 (3) Jagermeyr et al., 2015 (3) Jamieson et al., 1991 (3) Ko et al., 2009 (3) Leff et al., 2004 (3) Monteith et al., 1996 (3) Probert et al., 1998 (3) Ren et al., 2016 (3) Rosenzweig et al., 2014 (3) Rouse et al., 1974 (3)	Godfray et al., 2010 (13) Foley et al., 2011 (8) Garnett et al., 2013 (6) Gustavsson et al., 2011 (6) Rockstrom et al., 2009 (6) Tilman et al., 2011 (6) Cassman et al., 2003 (4) Galloway et al., 2008 (4) Li et al., 2009 (4) Parfitt et al., 2010 (4) Raun et al., 2002 (4) Van ittersum mk et al., 2013 (4) Cassman et al., 1999 (3)	Cordell et al., 2009 (3) Diaz et al., 2008 (3) Fargione et al., 2008 (3) Johnson et al., 2003 (3) Miao et al., 2006 (3) Peng et al., 2010 (3) Ramankutty et al.,2008 (3) Raun et al., 2005 (3) Ray et al., 2013 (3) Searchinger et al., 2008 (3) Seck et al., 2012 (3) West et al., 2014 (3) Wu et al., 2015 (3)

• Mueller et al., 2012 (4) • Ritchie et al., 1972 (4) • Arnold et al., 2012 (3) • Cabelguenne et al., 1999 (3) • Chen et al., 2010 (3) • Costa et al., 2003 (3)	• Stockle et al., 1992 (3) • Stockle et al., 2003 (3) • Taylor et al., 2012 (3) • Terribile et al., 2015 (3) • Willmott et al., 1981 (3) • Xu et al., 2010 (3)	• Cassman et al., 2002 (3) • Chen et al., 2014 (3)	• Yao et al., 2012 (3) • Zhao et al., 2013 (3)
Cluster 5: Land-use Changes (102 citations)		**Cluster 6: Emerging Technologies in Agriculture (86 citations)**	
• Foley et al., 2005 (11) • Kamusoko et al., 2009 (5) • Guan et al., 2011 (4) • Ipcc, 2014 (4) • Lambin et al., 2001 (4) • Parton et al., 1987 (4) • Schmidt-traub et al., 2017 (4) • Seto et al., 2012 (4) • Turner et al., 2007 (4) • Verburg et al., 2006 (4) • Busari et al., 2015 (3) • D'amour et al., 2017 (3) • Deng et al., 2008 (3) • Hanasaki et al., 2018 (3)	• Intergovernmental panel on climate change, 2019 (3) • Ipcc, 2007 (3) • Lal et al., 2004 (3) • Lawrence et al., 2016 (3) • Lepers et al., 2005 (3) • Muller et al., 1994 (3) • Myint et al., 2006 (3) • Pijanowski et al., 2002 (3) • Riahi et al., 2017 (3) • Saier et al., 2007 (3) • Sellers et al., 1997 (3) • Vitousek et al., 1997 (3) • Weng et al., 2002 (3) • Wu et al., 2006 (3)	• Priestley et al., 1972 (5) • Breiman et al., 2001 (4) • Dong et al., 2016 (4) • Gorelick et al., 2017 (4) • Ojha et al., 2015 (4) • Peel et al., 2007 (4) • Wheeler et al., 2013 (4) • Blaschke et al., 2010 (3) • Blaschke et al., 2014 (3) • Breiman et al., 1984 (3) • Brisson et al., 1998 (3) • Brisson et al., 2003 (3) • De groot et al., 2002 (3)	• Fao et al., 2017 (3) • Foody et al., 2002 (3) • Hall et al., 2009 (3) • Hansen et al., 2000 (3) • Hansen et al., 2013 (3) • Kussul et al., 2017 (3) • Moran et al., 1997 (3) • Mulla et al., 2013 (3) • Olofsson et al., 2014 (3) • Srbinovska et al., 2015 (3) • Tucker et al., 1979 (3) • Watson et al., 2014 (3) • Xiao et al., 2005 (3)
Cluster 7: Water-Food-Energy Nexus (84 citations)		**Cluster 8: Circular Economy (58 citations)**	
• Sterman et al., 2000 (11) • Bazilian et al., 2011 (7) • Biggs et al., 2015 (6) • Forrester et al., 1958 (6) • Barlas et al., 1996 (5) • Rasul et al., 2016 (5) • brundtland et al., 1987 (4) • Smajgl et al., 2016 (4) • Beall et al., 2011 (3) • Bizikova et al., 2013 (3)	• Chang et al., 2008 (3) • Endo et al., 2015 (3) • Fao et al., 2012 (3) • Keesstra et al., 2016 (3) • Sanders et al., 2016 (3) • Shi et al., 2005 (3) • Uen et al., 2018 (3) • Winz et al., 2009 (3) • Zhang et al., 2018 (3) • Zhang et al., 2017 (3)	• United nations, 2015 (7) • Steffen et al., 2015 (6) • Geissdoerfer et al., 2017 (5) • Atzori et al., 2010 (4) • Dahiya et al., 2018 (4) • Ghisellini et al., 2016 (4) • Lin et al., 2013 (4) • Arancon et al., 2013 (3)	• Blei et al., 2003 (3) • Genovese et al., 2017 (3) • Kirchherr et al., 2017 (3) • Lieder et al., 2016 (3) • Lipton et al., 2015 (3) • Merli et al., 2018 (3) • Sterman et al., 2001 (3)
Cluster 9: Shared Socio-Economic Pathways			
• Bandeau et al., 2007 (6) • O'neill bc et al., 2017 (6) • Van vuuren et al., 2011 (5) • Popp et al., 2017 (4) • Samir et al., 2017 (4) • Van vuuren et al., 2014 (4) • Alexandratos et al., 2012 (3)		• Bauer et al., 2017 (3) • Kriegler et al., 2012 (3) • Kriegler et al., 2014 (3) • O'neill et al., 2014 (3) • Rao et al., 2017 (3) • Rogelj et al., 2015 (3)	

4.4 Discussion of the results

Downstream of previous analyses, it is interesting to highlight the interconnections between the research clusters depicted in Table 1, produced through the descriptive clustering algorithm, and those shown in Table 9, produced through the co-citation analysis of cited references. The adoption of these two independent methods led to similar conclusions, thus confirming the robustness of the results obtained. Notably, adopting and integrating these two methodological approaches allowed us to develop a holistic overview highlighting the primary novel technological innovations to meet emerging sustainability needs, also laying the foundations for future research directions. According to both systematic and bibliometric analysis results, the use of simulation models in the environmental management of agribusinesses is critical to provide a scientific and data-driven approach to understanding, evaluating, and improving environmental practices (Table 1 – Cluster 1; Table 9 – Cluster 3). These models enable agribusinesses to assess and understand the environmental impacts of their activities, including the analysis of natural resource consumption, GHG emissions, and energy consumption. Indeed, it is possible to test different management strategies and identify those that lead to more efficient use of resources, both in terms of reducing waste and optimising production processes, improving both income and food sustainability. In addition to simulation models, our analysis revealed other kinds of technological solutions able to provide several environmental benefits, supporting the objectives of CE (Table 1 – Cluster 8; Table 9 – Cluster 8) and contributing to developing more flexible and resilient food supply chains (Table 1 – Cluster 3 and 6; Table 9 – Cluster 2). Notably, digital platforms can significantly reduce food waste by improving inventory management, facilitating food donations, implementing traceability systems, and facilitating direct communication with consumers to promote conscious purchasing practices. Another stream of research regards food waste valorisation; our investigation revealed the practice of exploiting food waste as a potential feedstock in biological processes to create various biobased products, as well as green chemicals and fuels. Further, digital technologies such as the IoT, big data analytics, and advanced tracking systems enable real-time visibility of foodstuffs throughout the supply chain. This visibility improves the ability to monitor and manage stocks, reducing the risk of errors, losses, and overstocking, avoiding the distribution of adulterated foodstuffs and certifying conformity with international standards. Regarding the farming stage, remote sensing technologies turned out to be critical in providing data for precision agriculture (Table 1 – Cluster 1 and 2; Table 9 – Cluster 5 and 6). The assessment of crops through satellite or aerial imagery makes it possible to optimise the use of resources, monitor and forecast crop yields, identify plant diseases, and improve overall soil management. Therefore, precision agriculture technology could reduce pollution and wasteful resource consumption, improve life quality, and contribute to achieving the SDGs, thus reducing the environmental impacts and improving the overall operational efficiency.

4.4.1 Literature gaps and future research avenues

Based on the analyses presented in the previous sections, we identify a set of gaps in the literature and propose some future research avenues on I4.0 and sustainability in the food sector.

The new I4.0 technological paradigm is reshaping how food firms' business models are structured in technological breakthroughs. According to Brenes et al. (2016), business models seem to affect a company's success or failure. For instance, there is empirical evidence regarding the customer use of food sharing platforms and their positive influence on food waste reduction (e.g., Michelini et al., 2020; Mazzucchelli et al., 2021). Therefore, food and agribusiness firms are increasingly developing and adopting new agile business models to satisfy customer expectations. The product-service systems (PSSs) are an archetypal example (Woolley et al., 2020). Because significant progress in sustainability necessitates behavioural changes, future PSSs will need to integrate issues of individual and social values with technical issues and relationships with the environment. As a result, future research might investigate new types of business models and PSSs and their influence on foodstuffs' sustainable consumer behaviour. Future PSSs could, for instance, include information on the product life cycle, on product environmental impact in all the stages of the FSC, as well as on product and ingredient traceability.

To effectively support the new agile business models, it is necessary to adopt versatile and highly integrated platforms that scale efficiently and quickly, and this requires the adoption of flexible and granular infrastructures. The new platform-based business models will establish communities, markets, and value, enabling interactions and exchanges between interdependent groups (Kloppenburg and Boekelo, 2019). This "platformisation" trend might be segmented along two axes: (1) digital technology to allow the exchange of data within the ecosystem; and (2) the development of value added through the scalability of the network of users and players of the platform, or rather the "direct network effect". As the network grows in terms of new users, the platform's value increases, since the value of the service provided for the single user can increase as more participants use the platform. Further, each new user gains from the platform's link to all current users and has access to all of the platform's innovations and services. Therefore, developing new food platforms that allow the complete traceability, transparency, and security of information relating to food products to all stakeholders in the supply chain (e.g., based on blockchain technologies) will be one of the main challenges of the next few years. Scientific research should therefore support practitioners in addressing this challenge. Integrating new technologies with those already existing and consolidated within the farm is also crucial to further investigation. Notably, this capacity becomes more effective as more stakeholders are involved in the integration process. Similarly, smart retrofitting, i.e., “transferring the aspects of the Industry 4.0 visions to machines and processes with the least possible financial and time expenditure” (Guerreiro et al., 2018), should also be investigated by future research since it might allow increasing companies' economic, environmental, and social outcomes.

Companies using I4.0 technologies on an ever-increasing scale to engage workers, customers, and suppliers in their ecosystems can enjoy more significant benefits and economies of scale (Müller, 2019). Therefore, horizontal integration in I4.0 necessitates data exchange with different partners outside the business. This kind of openness is very beneficial in terms of production agility and flexibility, but it poses the difficulty of keeping all stakeholders' data private and available only to those who need to know. Future research should develop trustworthy data exchange systems to maintain the privacy of the data as well as effective data governance mechanisms.

Furthermore, current literature is primarily focused on designing and implementing specific I4.0 technologies to monitor and enhance crop yields, preserve natural resources, and promote sustainable development (e.g., Dong et al., 2016; Gorelick et al., 2017). However, few investigations have been conducted on the influence of a mix of enabling technologies (e.g., blockchain, Internet of Things, and precision agriculture technologies) on food firms' economic, environmental, and social performance. Additionally, the few investigations published in the literature reported contradictory results. In order to further understand the connections between I4.0 and sustainability, as well as the advantages and challenges for their implementation and integration, future investigation on the topic may conduct multiple case studies involving semi-structured interviews with businesses implementing digital technologies and sustainable processes. Then, these relationships may be statistically verified by surveys on more prominent and representative groups. Long-term longitudinal studies may also be used to monitor the successful implementation of I4.0 technologies throughout the years.

Despite the potential benefits of adopting I4.0 technologies to reduce resource consumption and improve crop yields (e.g., Ojha et al., 2015; Srbinovska et al., 2015), recent research has shown that the emerging digital technologies could negatively impact sustainability performance, due to electronic waste and additional pollution generated by a higher use of electricity – see, for instance, the case of machine learning and artificial intelligence algorithms (e.g., Ejsmont et al., 2020; Beltrami et al., 2021; Balasubramanian et al., 2021). Therefore, future research should investigate strategies to mitigate the negative implications of I4.0 technologies on TBL sustainability.

Current literature on food sustainability evaluates the environmental implications of foodstuff production using the LCA approach (e.g., de Vries et al., 2010; Notarnicola et al., 2017). However, it is possible to use additional sustainability impact assessment measures. For instance, future studies could integrate the social and economic implications of the food products' life cycle using the Social Life Cycle Assessment (S-LCA) and the Life Cycle Costing (LCC) approaches (e.g., Guinee et al., 2011). These techniques enable interdisciplinary analyses, comparing economic, environmental, and social implications linked to different practices and technologies used in agriculture to boost crop yields. Future investigation should also focus on local food sustainability, supporting local economies to reduce food miles and carbon dioxide emissions (Kiss et al., 2019).

Finally, to successfully face the I4.0 transition, companies must necessarily change their mindset from a vision limited to individual areas of activity to a more holistic and transversal approach. Government policies could facilitate this paradigm shift, for example, by granting farms financing for I4.0-related investments. It follows that future studies should examine the role of institutions in promoting the I4.0 transition, evaluating the practical applicability of the measures by the companies and the resulting affordability of technologies.

4.5 Conclusions and implications

4.5.1 Theoretical contributions

This study provides a bibliometric and network analysis on I4.0 and sustainability in the food sector extending previous reviews (e.g. Wolfe & Richard, 2017; Portanguen et al., 2019; Eichler Inwood et al., 2019; Annosi et al., 2020; Turken et al., 2020; Corallo et al., 2020; Vågsholm et al., 2020; Kamble et al., 2020) in different ways.

First, the research goes further than a structured literary review in the field through the application of bibliometric techniques (i.e., performance analysis and science mapping) to detect the leading articles and the most frequent keywords according to co-citation and co-occurrence analyses, respectively. Second, performing an article co-citation analysis, this paper identifies nine main clusters (i.e., "ecosystem management", "supply chain management", "simulation models for environmental mangement ", "food production and food security", "land-use changes", "emerging technologies in agriculture", "water-food-energy nexus", "circular economy", "shared socio-economic pathways") related to particular research areas. These fields of science range from I4.0 technologies (cluster 3 and cluster 6) to sustainability issues (cluster 1, cluster 5, cluster 7, cluster 8, and cluster 9), while also considering supply chain and distribution (cluster 2) and food safety (cluster 4 and cluster 7). Third, the keywords co-occurrence analysis identifies the most frequent keywords of the research field, evaluating the relationship and the evolution of the keywords over time. Hence, this analysis allows for unveiling the actual state of the art of the literature on the topic. Furthermore, the frequently cited keywords, such as “sustainable development”, “simulation”, “food”, “land use change”, “big data”, “circular economy”, and “precision agriculture” match the research clusters mentioned above, paying attention to sustainability issues, and showing the importance of the new digital technologies to improve farming and food production.

Therefore, this research provides relevant contributions to theory. First, in order to identify the most significant papers, journals, researchers, institutions, and countries in terms of published articles and the total number of citations obtained, this study applies bibliometric and network analysis. Secondly, I4.0 and food sustainability researchers, educators, and other decision-makers could easily identify academics, organisations, and countries that deal with certain research interests. Interested scientists may propose joint research projects. Besides, these results are used by researchers and practitioners to classify the most influential contributions, research trends, and experts in the field.

4.5.2 Managerial insights for decision makers

This study provides several insights for governmental authorities and practitioners to maximise the benefits of digital technology in the food industry. Notably, such information is crucial for the managers of food companies since it enables them to innovate their business models and find solutions to currently pressing issues. Indeed, the nine-clusters classification allows farmers and food companies' managers to (1) evaluate the existing I4.0 status in food technology and its impact on environmental sustainability and (2) define, in each cluster, the most relevant requirements for making appropriate choices about using current I4.0T for sustainability. This study provides multiple examples of technologies that may be employed and combined to enhance logistics and production systems in terms of TBL performance. Notably, agribusinesses must create an efficient internal and external system of cooperation and synergy to promote the sustainability culture across all levels of the organisation and the entire FSC, emphasising how adopting such a new technological paradigm is a long-term investment that will benefit the environment and help achieve economic objectives.

Furthermore, the estimated increase in food demand in the coming years requires particular attention from institutions and stakeholders. In this regard, this research would also be useful in identifying the most prominent research centres and institutions for strategic partnership to be financed by companies and governments. The results from this study might have significant impacts on regional and national growth concerning the implementation of the new digital technology throughout the FSC to boost agricultural yields and lower carbon footprint.

4.5.3 Limitations and future research directions

Although considerable attention has been paid to ensuring validity and reliability of the results, some limitations must be acknowledged. *First*, in the initial search, only documents published in the WoS database have been considered, excluding additional databases such as Scopus or Google Scholar. Hence, future research could compare and integrate other databases outcomes. Further, we only considered articles and reviews published in peer-reviewed journals and excluded other publication types (e.g., conference proceedings and technical reports). *Second*, we implemented the co-citation analysis of cited references and the keywords co-occurrence analysis using VOSviewer software, while other statistical and clustering methods and software could be used. Besides, this study performs co-citation and co-occurrence analysis, but also further analysis could be implemented, such as co-authorship analysis.

While we have few constraints, this study contributes to the I4.0 and food sustainability literature and provide research opportunities for those who want to investigate these topics. We hope that this extensive framework will help integrate the promising scientific research outcomes and ideas into advancing digital solution thus digitising and optimising the food industry.

5. How can a circular and digitized value chain mitigate food loss and waste? A multiple case study from the Italian agri-food industry

The systematic and bibliometric analysis of the literature revealed a dearth of holistic studies assessing how a mix of digital technologies, such as blockchain, the IoT, and big data analytics, affect the agri-food industry's sustainability challenges, such as FLW mitigation. FLW in agri-food value chains pose a serious barrier to sustainable development, since they directly affect the consumer economy, deplete natural resources, and generate GHG emissions. Indeed, when foodstuffs are lost or wasted, the resources employed in their manufacturing and distribution along the value chain, such as land, water, and fuel, are also wasted (Krishnan et al., 2020). Notably, FLW is responsible for about 25% of the water used by agriculture annually, 23% of all croplands, which is equal to all of Africa's cropland, and generates 8% of the world's yearly greenhouse gas (GHG) emissions (Teigiserova et al., 2020). Integrating I4.0 technologies with CE practices has been hailed as a suitable route for agribusinesses to reduce FLW. Based on the above evidence, through the theoretical lens of Institutional theory and Resource-based view, this Chapter aims to answer RQ2 (*How are agribusinesses redesigning their supply chain to fulfil increasing stakeholder demands for effective food loss and waste mitigation?*) by conducting a qualitative multiple case study involving 20 purposeful sampled Italian agribusinesses engaged in the sustainable and digital transition. Semi-structured interviews were used to gather data, then supplemented with secondary data to provide our investigation with a more comprehensive perspective. This analysis identifies the main causes generating FLW along the value chain and the main external and internal drivers influencing the growth of circular and digitalised agri-food business models. Recognising these factors is the first step to embarking on a virtuous path leading to agri-food industry sustainability. Policymakers may enact less stringent regulations on food by-products and expiry dates and boost the role of sustainability drivers, supporting food security and the development of more sustainable value chains. In addition, the degree of implementation of digital technologies and circular initiatives in the agri-food sector is explored, revealing their benefits and practical constrictions, thus significantly contributing to the knowledge of the research field. Finally, by highlighting the impact of the implemented strategies and innovations on corporate performance, particularly on environmental outcomes and FLW mitigation, this study provides a thorough framework for agri-food businesses looking to interface with Industry 4.0 and CE paradigms. To accomplish this goal and redesign their supply chains during times of transition, agribusinesses' managers must entirely rethink their operational approaches and adopt a philosophy that keeps long-term shared value creation ahead of short-term efficiency and profit.

5.1 Theoretical underpinnings

5.1.1 Institutional theory

The Institutional theory assesses how a firm's external forces impact its business model and practice (Hirsch, 1975; Chan et al., 2020). This theory assumes that organisations work within a network of values, norms, rules, and beliefs that guide their operations; these are social constructs that are established over time and delineate the entire scope of business operations (Meyer and Rowan, 1977). According to Latif et al. (2020), managers become aligned with their institutional environment in order to increase the chances of business survival because by conforming to social expectations they gain approval, which is the central principle of institutional thinking. It follows that firms' social, environmental, and economic performance is strongly influenced by the institutional context in which they operate. The basic premise of the Institutional theory is that institutional mechanisms exert pressure on individual firms, resulting in isomorphism. Notably, isomorphism is a constraining process that drives a unit, part of a certain population, to resemble other units facing the same set of environmental conditions (DiMaggio and Powell, 1983). At the organisational level, this term suggests that organisational characteristics change to adapt to the external environment. According to DiMaggio and Powell (1983), there are three different types of isomorphic driving forces: coercive, mimetic, and normative. These pressures can be exerted by different stakeholders, such as government organisations, suppliers, customers, and non-governmental organisations. Coercive pressure is exerted by external parties, such as government authorities, through laws, acts of persuasion, or invitations. This isomorphism forces companies to implement environmental regulations and standards, subject to sanctions and punishments. Further, due to normative pressure, firms are required to meet the demands of professional networks. As a result, normative isomorphism is caused by the pressure to conform to society and industrial standards. Finally, mimetic pressure arises when companies engage in competition in search of better performance than other businesses. This pressure typically arises in an uncertain environment and results from imitative processes. It is fundamental for firms to respond to the actions and behaviours of their competitors. Thus, firms seek to follow the example of others, perceived as more legitimate competing firms. All these isomorphic pressures can lead to the implementation of sustainability reports as well as practices to reduce the use of natural resources, reducing the overall impacts on the environment.

5.1.2 Resource-based view theory

The Resource-based view aims to explain and predict the reasons why companies achieve a competitive advantage. The theory aims to understand, for example, why one company succeeds in having higher profits than another and what makes a competitive advantage sustainable in the long term. Consequently, in contrast to the Institutional theory, the focus here is on the internal resources of the company to identify the resources and competencies capable of generating competitive advantages. Penrose (2009) defines the company as a container of tangible and intangible resources enabling companies to differentiate themselves from others. When this approach is applied, the company is defined in terms of resources and capabilities rather than markets served (Andersen and Suat Kheam, 1998).The main assumption on which the theory is based is that managers can learn to manage influences from the external environment through their skills and knowledge. Barney (1991) defines resources as something that must "possess value, be rare, not perfectly imitable and not perfectly replaceable," and reside in the knowledge and expertise of people. The most significant resources are the intangible ones, i.e. those resources that by their nature cannot be sold or transferred, are not imitable or substitutable, and, therefore, represent the key factor for gaining a competitive advantage; these resources can be, for example, knowledge or reputation, from which the approval of companies derives. Therefore, according to the Resource-based view, the competitive advantage and the attainment of certain results do not only come from the external needs involved in formulating strategy but what matters more broadly are the intrinsic characteristics and potential of each company (Penrose, 2009). From the perspective of a whole supply chain, it is necessary to enhance coordination with all the actors of the supply chain, having a shared and lasting vision between the resources of the company and all its stakeholders (Hart, 1995), acquiring technologies and strategic knowledge from suppliers, and forming strategic partnerships (Carter and Rogers, 2008). In order to build a sustainable competitive advantage over time, companies need to build their strategies depending on environmental objectives. This is referred to as the natural Resource-based view, according to which companies must possess three interconnected strategic capabilities: pollution prevention, product management and sustainable development (Andersén, 2021). These capabilities involve selecting raw materials with the lowest possible environmental risk, designing the product to minimise environmental impact, and redesigning existing products to suit environmental objectives.

5.1.3 Green supply chain and innovation research

In recent years, there has been a rising acknowledgement of the need for green innovation to mitigate the environmental impact generated by organisations and attain sustainable development (Chen et al., 2018). Technological developments that decrease energy usage, prevent pollution and allow waste recycling are all possible examples of green innovation, encompassing green product design and business environmental management (El-Kassar and Singh, 2019). Previous research showed that green innovation could effectively enhance corporate environmental, economic, and social performance. Notably, the impact of green innovation on businesses' outcomes depends on the national context in which the organisation operates and the management of internal resources (Aguilera-Caracuel and Ortiz-de-Mandojana, 2013; Fiorini et al., 2022). Consequently, the Institutional and Resource-based view theories have been widely adopted as the theoretical underpinning for many empirical studies on green supply chain and innovation research. For instance, different studies developed an analytical model to empirically examine how institutional driving forces affect businesses' adoption of GSCM practices and how such factors affect corporate economic, environmental, and social performance (e.g. Saeed et al., 2018; Ueasangkomsate and Pornchaiwiseskul, 2019; Zhang et al., 2020; Samad et al., 2021). Other researchers used institutional pressures as moderating factors to analyse the link between GSCM strategies and corporate outcomes (e.g. Zhu and Sarkis, 2007; Kalyar et al., 2019). Further studies examined the moderating effect of cutting-edge digital technologies, including big data analytics, on the links between institutional forces, GSCM practices, and business performance (e.g. Bag et al., 2022; Shahzad et al., 2022). On another note, using the Resource-based view perspective, Graham et al. (2023) investigated the mediating role of employee engagement in the relationship between GSCM procedures and environmental outcomes, while other researchers empirically tested the relationships between human resource management, green innovation, and environmental performance (e.g. Singh et al., 2020; Sobaih et al., 2020; Niazi et al., 2023). Further studies analysed the mediating role of research and development intensity on the link between green innovation and firm performance (e.g. Duque-Grisales et al., 2020; Lin et al., 2021). Other research investigated the mediating role played by green innovation between corporate social responsibility strategies and environmental performance (e.g. Kraus et al., 2020; Simmou et al., 2023). Moreover, by combining the Institutional theory and the Resource-based view, Li et al. (2020) provided insights into the link between external driving forces, GSCM practices, and performance under the moderating effect of quick response (QR) technology, while Huang and Chen (2022) analysed how external pressures and a firm's green slack influenced enterprises' desire to develop green products and achieve superior outcomes. Further researchers investigated the impact of different internal and external factors (e.g. top management support, green motivation, institutional pressures, and environmental orientation) on the adoption of GSCM practices (e.g. Muduli et al., 2020; El-Garaihy et al., 2022). Finally, Qin et al. (2022) investigated the influence of internal environmental management and green information systems on adopting GSCM practices and their resulting effect on FSCs' organisational outcomes.

Therefore, the existing research on GSCM and green innovation focuses primarily on theory testing, examining the relationships between institutional driving forces (i.e., coercive, normative, and mimetic pressures), internal resources (e.g. human resources, top management, and environmental orientation), green practices (e.g. green purchasing, green shipping, and eco-design), and environmental and economic performance (e.g. mitigation of pollutants, improved brand value, and increased profits). Just a few theory-building studies (e.g. Liu and Yan, 2018; Kim et al., 2016) have examined how external and internal driving factors are influencing the structure of the present supply chains to support green innovation and fulfil the emerging demands of sustainability and digitalisation.

5.1.4 Food loss and waste management

During the last 10 years, research on FLW management has increased. Most of these studies investigated the amount of FLW generated in the different FSCs, determining how much each actor is responsible for the issue. According to Kummu et al. (2012), food loss occurs upstream of the value chain during agricultural production, postharvest, and processing, while food occurs downstream during distribution and consumption. Notably, between 46% and 65% of the total FLW generated by the FSC is attributable to food waste at the household level, with the remaining portion coming from other parts of the value chain, such as agriculture, manufacturing, and distribution (Annosi et al., 2021). Kusumowardani et al. (2022) argued that CE practices could be applied to food waste management at all stages of the food chain, proposing a modified version of the waste hierarchy, where the first useful option is to avoid producing food surplus. Notably, based on the CE paradigm, Sehnem et al. (2021) proposed six levels of actions to be applied to minimise waste: (1) prevent avoidable waste and avoid producing excess food; (2) attempt to reuse unavoidable waste first for human consumption and, if not possible, for animal consumption; (3) recycling for industrial use, anaerobic digestion, composting and combustion for energy recovery; (4) landfill, which represents the least desirable route and to be used only when the upper levels are not feasible. This hierarchy could be a valid guide to how to adopt practices for a sustainable transition (Ciccullo et al., 2021). The first two options must be a top priority, as they allow for limiting the use of natural resources, reducing GHG emissions, and promoting food security. This is what emerged from the analysis conducted by Papamonioudis and Zabaniotou (2022), in which two successful practices of reuse and redistribution were identified, i.e. the possibility to either repackage and sell through promotional campaigns and discounts or redistribute to specific food aid associations. In addition, there are various studies on how the use of digital technologies can help solve FLW issues throughout the supply chain. Irani et al. (2018) argued that big data analytics could aggregate data to prevent FLW and better analyse the quantities of food lost or wasted at different value chain stages. De Souza et al. (2021) suggested an innovative solution based on the combination of artificial intelligence with machine learning, supporting decision-making with less human involvement and improving sales forecasting and management. In addition, by facilitating product identification, tracking, and tracing across the value chain phases, IoT and blockchain could significantly enhance food safety, a key worldwide issue (Abbate et al., 2023a). Notably, using IoT and sensors, it is possible to keep track of the condition of products in the FSC, thus reducing the amount of FLW due to changes in temperature and humidity (Ada et al., 2021). Nonetheless, agribusinesses throughout the world continue to struggle to deploy new digital technologies and CE practices, mostly owing to a lack of modernisation and automation (Konur et al., 2021; Ali et al., 2022).

5.1.5 Research objectives

The potential of combining I4.0 enabling technologies and CE initiatives to mitigate FLW has not yet been properly examined, needing further investigation (Lopes de Sousa Jabbour et al., 2018a). This integration would help agribusinesses' sustainable and technological growth, achieving positive outcomes in profit and environmental protection. As a result, the need to investigate the effective degree of implementation of these practices and technologies to enable FLW reduction and promote the digital and sustainable transition of the agri-food industry. In addition, prior research has solely focused on individual agribusinesses (e.g. Goonan et al., 2014), ignoring the processes involving other players along the FSC. However, to better understand the causes generating FLW and the reason why specific practices and technologies for its mitigation are implemented or not, it is necessary to investigate beyond specific entities and their deliberate choices and instead adopt a more comprehensive perspective of overall organisational processes.

This study aims to cover the above-mentioned research gaps by investigating how agri-food companies are redesigning their supply chain, in terms of digitisation and CE strategies, to fulfil increasing stakeholder demands for effective FLW mitigation and sustainable development. Notably, we aim to examine what tools individual organisations employ to mitigate FLW, as well as the sequence of actions established by the different supply chain actors to prevent inefficiencies. The study's findings are interpreted through the Institutional and Resource-based view theories, which represent an appropriate theoretical lens for explaining the internal and external pressures leading to sustainability implementation (Bag et al., 2021).

5.2 Methodology

This study adopts the multiple case study research approach. This decision is justified for different reasons. First, it is an excellent research approach to explain and investigate novel phenomena (Eisenhardt, 1989). Indeed, there is little existing knowledge in the scientific literature concerning the research topic under consideration, i.e. the integration of I4.0 technologies and CE practices for effective FLW prevention and management in the Italian agri-food industry. As a result, this exploratory analysis aims to accurately understand a specific phenomenon in its peculiarity and uniqueness (Stake, 2008). Additionally, multiple cases are preferred to a single case since they are more likely to offer convincing explanations (Yin, 2014). Notably, by investigating multiple cases, it is possible to compare different businesses and analyse the results in a broader view, achieving more robust results (Corcoran et al., 2004).

5.2.1 Case selection

We employed the purposeful sampling technique, which is widely used in qualitative research for identifying and selecting information-rich cases related to the phenomenon of interest to maximise efficiency and validity (Suri, 2011). The steps involved in this method include establishing a set of criteria, researching cases, contacting potential interlocutors, and checking if all the criteria have been satisfied.

Therefore, the first step was to define selection criteria, consistent with the topic and research objective:

1. Preparation of interviewees on the raised issues. Through this preliminary survey, we were able to evaluate the respondents' ability to answer the questions and provide the groundwork for the subsequent validity of the information obtained from the interviews. Respondents were assured of their complete privacy before participating in the study.
2. Food loss and waste awareness: the firm must take actions to prevent and reduce FLW, promoting food security.
3. Industry 4.0 and Circular Economy implementation: the company must adopt digital technologies and CE practices to prevent and reduce FLW and support sustainable development.
4. Geographic area: the company operates and implements its strategy in Italy.

The second step was to research agri-food companies for our case study. We particularly targeted Italian firms listed among the most innovative and environmentally responsible Italian enterprises in agri-food magazines. Companies were contacted initially by email or phone to confirm their compliance with all the selection criteria. We also checked their websites in-depth to verify the adherence to requirements. In total, we identified 102 potential candidates for the analysis. Among them, 63 companies met all the selection criteria. Because of scheduling constraints, 16 CEOs declined to participate, while the others gave informed consent to conduct interviews. We continued collecting data until we reached theoretical saturation, achieved when there was no new data and no new themes, and it was possible to replicate the study (Fusch and Ness, 2015). Finally, we selected 20 agri-food companies. This final sample contains heterogeneous firms in both type and geographic location (i.e., North and South of Italy). Notably, we interviewed companies from different value chain stages, including manufacturers, distributors, and retailers. In addition, micro, small, medium, and large enterprises were interviewed, including some family firms. This allowed us to obtain a broad perspective of the phenomenon under investigation. A pilot case was chosen to conduct a preliminary interview to validate the protocol and proceed with the data collection process. Table 10 highlights the demographic information of the final sample of companies.

Table 10. Sampled companies

Case ID	Description	No. of employees	Turnover (million Euros)	Interviewee's role	Geographical Location
Firm A	Baked foods and chocolate production	>250	12.700	Sustainability manager	North
Firm B	Ice cream and frozen foods production	>250	397	Sustainability analyst	North
Firm C	Coffee production	>250	180	Quality and environmental management system development manager	South
Firm D	Frozen food processing and storage	<250	100	Quality manager	South
Firm E	Pasta production	>250	150	Quality manager	South
Firm F	Food retailer	>250	4.000	Sustainability manager	North
Firm G	Food production and distribution	>250	1.900	Sustainability manager	North
Firm H	Food distribution	>250	486	Sustainability manager	North
Firm I	Frozen food products	<250	60	Quality manager	South
Firm L	Beef and pork production	>250	3	Sustainability analyst	South
Firm M	Semi-finished products and preparations of fruits and vegetables	<50	30	CEO	South
Firm N	Pasta production	<250	70	Environmental and manufacturing manager	South
Firm O	Farming business	<10	0.5	CEO	North
Firm P	Packaging production	<250	1,5	Certification manager	South
Firm Q	Ice cream production	<50	3	Quality assurance and manufacturing manager	North
Firm R	Milk products production	<50	3	CEO	North
Firm S	Packaging production	>250	122	Marketing and communication manager	South
Firm T	Cold cuts and fresh food production	<250	80	Sustainability manager	North
Firm U	Egg production	>250	700	Sustainability manager	North
Firm V	Pasta production	<250	87	Plant manager	South

5.2.2 Data gathering

We adopted the qualitative semi-structured interview technique to gather primary data. In particular, we conducted semi-structured interviews between September 2022 and January 2023, with an average duration of 45 minutes. To embrace diverse perspectives, we interviewed employees from various roles (e.g., CEO, sustainability manager, and marketing manager). According to Yin (2014), data collection began with the preliminary definition of a protocol to be followed to improve internal validity. As the interviews were semi-structured, the sequence of topics to be discussed and analysed was established, defining key points to be covered and leaving the discussion open-ended; the questions were then adapted and contextualised to the different companies. This choice of interview allowed us to remain focused on the topic, leaving the interviewee free to discuss the topics to be explored in depth as they felt they were most important. Notably, the interview protocol was divided into the following three sections: (A) interviewee and organisation characteristics (e.g., interviewee's role, number of employees, firms' turnover); (B) how FLW are managed and addressed in the organisation (e.g., implementation of CE practices and industry 4.0 technologies); (C) influence of internal and external stakeholders (e.g., government, customers, top management). Interviews were transcribed verbatim (Cillo and Verona, 2008) and were sent later to the interviewees to ensure their accuracy and to collect any additional information (Roeck et al., 2020). When we noticed discrepancies or lack of information, we contacted companies by e-mail or phone for further details (Demeter and Losonci, 2019). In addition, primary data provided by respondents were triangulated with secondary sources, such as corporate data, websites, sustainability budgets, and strategic reports (De Massis et al., 2015).

Furthermore, we employed the data triangulation approach by integrating several sources to enhance the construct validity (Roeck et al., 2020). Therefore, primary data provided by respondents were triangulated with secondary data sources, such as sustainability reports, project documents, and corporate websites. Finally, reliability was ensured through a case study database to organise all primary and secondary sources and subsequently carry out the analysis.

5.2.3 Data analysis

Thematic analysis (TA) was conducted to elicit emerging themes and categories (Braun and Clarke, 2006). To facilitate a systematic coding approach, we used NVivo 12 software. Two researchers have independently read and coded the interview transcripts and corporate documents. To enhance the study's external validity, the researchers employed a within-case analysis for each organisation profiled and a cross-case analysis to highlight similarities and differences between cases (Eisenhardt, 1989). Notably, the TA procedure involved different steps. The first step was to read the material multiple times to familiarise with it. Second, we summarised the essential aspects of the data that pertained to the theoretical investigation by developing first-order codes. Step three was to combine first-order codes into provisional categories. We coded the data to determine if it corresponded to the emerging theoretical categories. If not, we checked the data that did not fit and adjusted the classifications. Step four combined first-order codes into second-order themes. Then, we had to focus on each recognised topic, consolidating theoretical elements and naming and describing them precisely. Thus, by merging second-order themes, we assessed the cohesiveness of the whole framework and reached the aggregate theoretical dimensions (step 5). The last step consisted of writing an academic report of the analysis by using convincing interviews' excerpts to support the assertions made. The cross-case analysis results are highlighted in Figure 10.

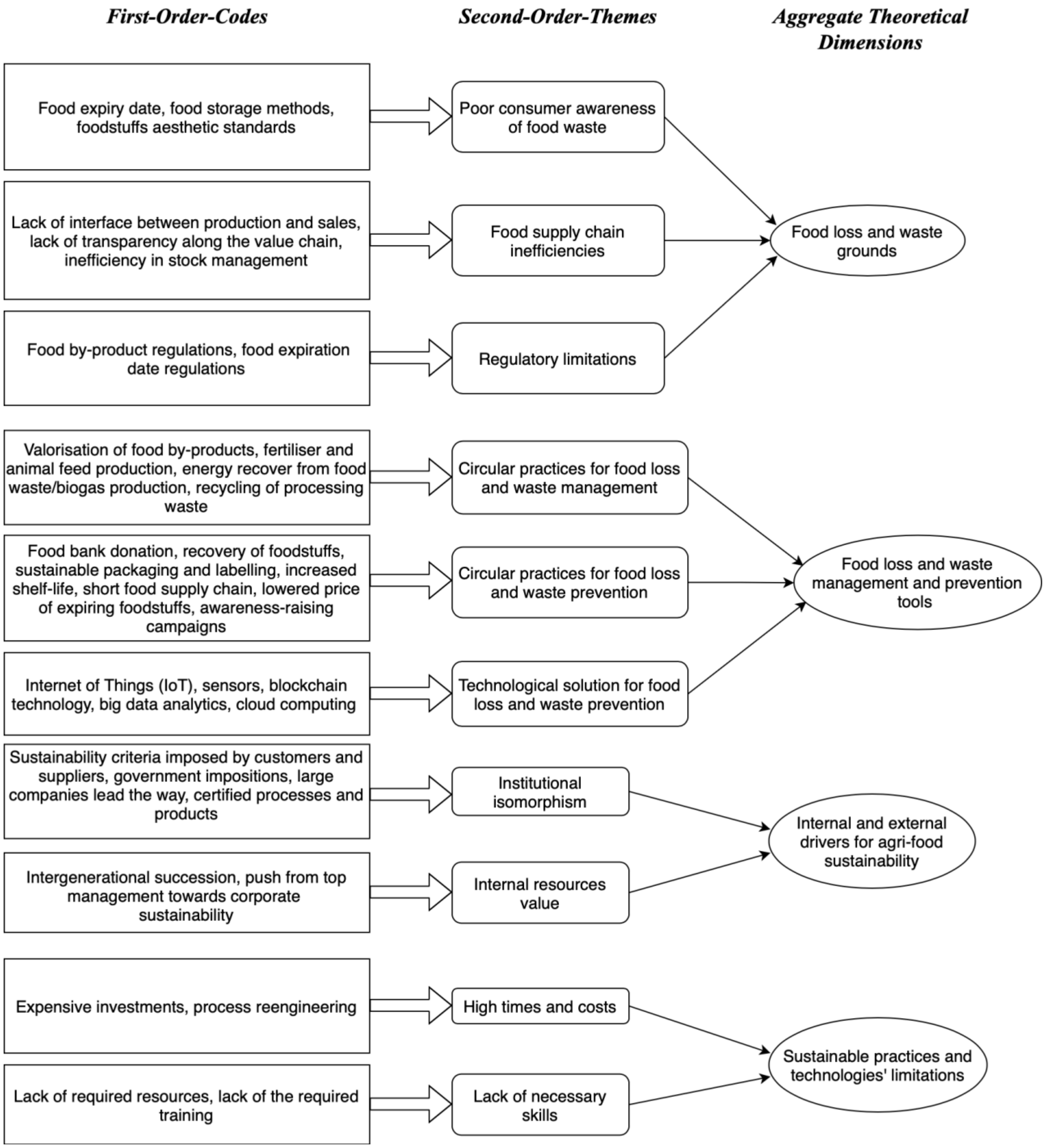


Figure 10. Data structure overview

5.3 Findings

The major themes and sub themes that emerged from the analysis of qualitative data are presented in the sub-sections below.

5.3.1 Food loss and waste grounds

The analysis showed that there are still many problems related to FLW in the whole value chain. However, many issues are directly related to consumer attitudes and behaviours towards FLW. Significant waste is generated during the sale and consumption phase by limited shelf-life and poor consumer awareness about expiration dates food storage methods. According to European Commission (2018), about 10% of all food wasted is associated with misunderstandings of the expiry date. The current food labelling system reports two types of wording: 'best before' and 'use by', as some foodstuffs maintain their optimal microbiological and organoleptic qualities even after the minimum shelf-life (Priefer et al., 2016). However, consumers prefer to throw them away, as this information should be better clarified. This problem is also due to the current regulations (European Commission, 2011), according to which foodstuffs cannot be sold if they have passed their expiration date and are therefore disposed of despite being perfectly edible in certain cases. These aspects are exemplified by the following quotes:

> *The product's quality is often affected by the way it is stored [...] it would be useful to indicate on the packaging what would be the right way to store the product while maintaining its properties [...] Thorough validated analyses, we declare that our product, which has a shelf-life of 2 years, if it is stored at the correct temperatures, which are about -18/-22 °C, even after two and a half years or after three years, it does not suffer organoleptic or microbiological problems. Therefore, it can be consumed [...] In recent years, the awareness has grown that that expiration date is indicative, but there is still much work to do to avoid consumers throwing away edible food. (Firm Q).*

> *The issue of consumer education is very important [...] The retail chain cannot sell a product that has passed the expiration date because the law says it cannot [...] The fact that a product is still good despite having passed the expiration date is irrelevant to the law. (Firm F).*

Furthermore, another significant problem is due to the strict Italian food by-product regulations (D.Lgs. 152, 2006). Bringing a food product into the by-product category is very tricky, as it must have specific characteristics, as stated by the company manager of Firm C:

> *Current regulations on food by-products are very stringent [...] Different valuable goods cannot still be classified as a by-product, even though these may have characteristics and fibres that could safely be used for animal feed or as a food ingredient [...] This is what happens in particular with silverskins that are rich in soluble fibre and could safely be used as a food product. (Firm C).*

In addition, a significant percentage of food waste is generated because certain products, especially fruits and vegetables, are discarded as they do not conform to aesthetic standards. Consumers prefer to purchase foodstuffs products that appear aesthetically pleasing. This happens because the consumer considers the product's aesthetic appearance a quality variable (Kuosa, 2021). It often stems from imprinted habits handed down by parents or government-mandated standards. Indeed, current regulation imposes specific aesthetic standards on fruit and vegetables, limiting the purchase and consumption of products that have spots, deformations, but are completely edible (European Commission, 2021b). However, as highlighted by the CEO of Firm O, food aesthetic is not always a quality parameter:

> *Everyone looks at fruits and vegetables outside, but some are composed almost entirely of water [...] Take a zucchini as an example: this has about 96% water, so if it is ugly outside but is grown with clean water, then we are eating something healthy, but if it is perfect outside and the water it is grown with is full of pesticides, we are eating something unhealthy. Thus, we should educate the consumer that the value of a food product is not always due to its aesthetics but rather how it was produced and what the farming methods were. (Firm O).*

Furthermore, the analysis highlighted poor collaboration and information sharing between the different actors in the FSC, thus leading to overproduction and food waste generation. However, as the interviewees explained, it is challenging for agribusinesses to share information with other levels of the supply chain. FLW also occurs due to non-transparent relationships between food manufacturers and retailers; therefore, monitoring and collaborating across the entire supply chain should be prioritised to align all objectives towards sustainability (Santagata et al., 2021). Notably, farm managers argue that there is a great distance between them and manufacturing companies; thus, it would be necessary to establish a long-term collaboration to increase sustainability.

> *Our customers are often so far from our business, thus from the farming stage [...] The result is that more food is often ordered than is needed to meet demand, consequently generating avoidable waste [...] We have pushed manufacturing companies to promote an Italian national cultural plan, with the aim to avoid the excesses of production that lower the market value. (Firm O).*

An additional problem regards stock management; in fact, many problems arise from the rotation of certain products in stock and the way they are stored. It is especially true for perishable products (Piva et al., 2022). No company uses digital technologies or systems that can offer a comprehensive overview of the stock, considering expiration dates and perishability. I4.0 technologies could help by using smart warehouses to alert the manufacturer to the condition of specific products, the breakdown of a refrigerator, or problems that may arise during storage.

> *If our stock of seasonal fruit is too high, each day that it remains unsold gradually reduces its shelf-life [...] In the worst case, the fruit will eventually rot, and the company will have no choice but to throw it away. (Firm F).*

As a result, this analysis sheds light on the primary causes generating FLW across the agri-food value chain. Notably, FLW were found to be mainly dependent on consumer-related factors (i.e. poor consumer awareness towards the expiry date and food storage methods, as well as high aesthetic food standards), intra- and inter-organisational level factors (i.e. stock management inefficiencies and poor collaboration and information sharing across the supply chain actors), and meso-level factors (i.e. legislation inhibiting FLW mitigation).

5.3.2 Food loss and waste management and prevention tools

Furthermore, one of the most critical themes that emerged from the analysis concerns the wide dissemination and adoption of CE practices to enhance the value of FLW throughout the supply chain. According to Parfitt et al. (2010), inevitable food losses should be reused as a by-product, and it is what the companies interviewed are managing to do. All by-products are typically recycled and recovered for different applications: machinery maintenance, animal feed and fertiliser production, and sustainable energy generation from biogas and bioliquids. Additionally, whenever possible, processing scraps are reintegrated into the production process, minimising the amount of waste. This exemplified by the following quotes:

> *The whey is used to clean the machinery from where the milk comes out since it has a good percentage of acid and, above all, allows the bacterial flora necessary for fermentation to be maintained [...] If we used classical detergents, all bacteria would be eliminated and the right ripening would not take place [...] The ripening of cheese is determined by lactic acid bacteria, so cleaning with whey allows us to work in a natural way (Firm R).*

> *We recycle food waste for various purposes, such as to produce natural fertiliser [...] We also send a part of the waste to a biodigester for biogas production, which can be used in turn to produce both electrical and thermal energy. (Firm O).*

> *We have a cogeneration plant fuelled not by biogas but by bioliquids, which are nothing but dripping fat residues, the slaughterhouse waste, called sebum, which is dripped and introduced, after refining, into the plant. This sebum is certified as a sustainable energy source. (Firm L).*

> *The production that cannot be released to the market is put into the by-product chain and is used as animal feed, improving both environmental and economic outcomes [...] We also implement product rework practices [...] If there is a processing defect, we take the product back to its origins, so to the beginning of the production process, with a shredding and grinding process [...] A recoverable food waste cannot be allowed to be discarded, also for an environmental issue because significant energy resources were used to produce it. (Firm N).*

Moreover, one widely adopted practice is food surplus donation to avoid waste. Food surplus from retailers or producers should be available through alternative pathways (Horoś and Ruppenthal, 2021). Almost all the companies interviewed have formed partnerships with associations that help them distribute food surplus. Typically, donation regards redundancies from the ordinary production of highly perishable foods that would otherwise have to be disposed of. In addition to charity, agribusinesses aim to mitigate FLW through collaborations and projects with innovative organisations and startups committed to food sustainability, thus improving economic performance and contributing to achieving SDG 2, "zero hunger". These aspects are exemplified by the following quote:

> *There may be products that do not reach the consumer, for example, because the cans of tuna present some dents or because retailers do not accept products that have a shorter shelf-life than what they require [...] For all these categories of products, so edible, safe and healthy, we donate them to the Food Bank [...] Recently we made an estimate: in 2021, we donated more than 4 million cans of tuna, we have collaborated with them for about ten years, and in these years, we have contributed to the nutrition of more than a million people [...] In addition, we have been collaborating with Too Good To Go, offering the possibility of recovering and selling expiring foodstuffs that cannot be integrated into traditional channels, avoiding throwing them away. (Firm G).*

In addition, packaging is a central element related to implementing CE practices. In recent years, companies have been adopting biodegradable, recycled and/or recyclable packaging, lowering the environmental impact, improving foodstuffs preservation, and increasing shelf-life (Do et al., 2021), with significant efforts also to reduce the number of materials used to achieve single food-contact packaging. Further, companies' commitment towards environmental protection is reflected in the use of sustainable labelling (Aitken et al., 2020a). According to the interviewees, it is applied to the product's packaging to communicate the firm's core environmental projects to the final consumer. As a result, sustainable packaging as a whole is used to raise consumer environmental awareness and highlight the differences between the specific company's product and that of its competitors. These aspects are reported in the following quotes:

> *Regarding the communication through the label, both on the packaging of tinned meat and hamburgers, there is the Environmental Product Declaration showing the product sheet and the LCA of our food goods [...] Therefore, our packaging also aims to highlight the distinctive features of the product and raise consumer awareness towards environmental issues. (Firm L).*

> *We always look for packaging that reduces environmental impact and favours recycling or compostability at the end of the product's life. Currently, we use poly-coated paper packaging, a solution that offers good results in reducing environmental impact and safeguarding the product [...] This material is indeed easily recyclable, biodegradable, and compostable. (Firm B).*

> *Sustainability of packaging is one of the objectives of the company's management system; in fact, we have worked on lightening packaging materials and reducing scraps during the packaging process [...] This allows the company not only to be more environmentally friendly but also to reduce costs due to raw materials purchasing. (Firm C).*

> *With a circular economy perspective, we aim to increase foodstuffs' shelf-life by designing and using appropriate packaging [...] This is especially the case for chocolate in equatorial areas, as in geographical locations where it is a very high temperature there is special packaging in which the product is completely sealed to avoid organoleptic or microbiological problems. (Firm A).*

Notably, concerning households' education, companies are also active in various projects to increase consumer awareness towards food waste mitigation, as explained by the sustainability manager of Firm G:

> *We are working on consumer education to reduce waste [...] There is, unfortunately, still the habit, when opening the can, of throwing the oil down the sink, when the oil we use is of very high quality and is also rich in nutrients because it has been in contact with the tuna. (Firm G).*

Furthermore, some companies are committed to promoting local foodstuffs, arguing that this contributes to achieving environmental and social sustainability. The SFSC can improve traceability and transparency, as fewer intermediaries make it easier to trace back all information, limiting the risk of waste (Kiss et al., 2019). Further, the short supply chain focuses on the development of the territory and decreases the implications of the aesthetic food standards, which are not considered essential for organic and zero-mile products. This is shown by the following quotes:

> *The short supply chain contributes to a lower environmental impact thanks to reduced food miles, but it also tries to promote less standardised food varieties, so local foodstuffs [...] On the one hand, it means working on biodiversity. However, on the other hand, it clearly means having relationships with local firms, promoting social sustainability [...] Giving the final consumer a product made by a local company contributes to its growth. (Firm F).*

> *The short food supply chain has allowed us to share best practices with suppliers and customers, facilitating technological innovation while also avoiding food waste because, since there are fewer intermediaries compared to a traditional supply chain, all food is handled less. (Firm L).*

> *We have observed that consumers of local food products are more willing to buy less beautiful items, perhaps because they are distinctive and perceived to be healthier. (Firm F).*

As a result, a short and local supply chain can concretely help in reducing FLW generation. This practice is usually adopted by small businesses, which seek to network with local producers to source fresh raw material grown without mineral fertilisers or chemical pesticides. Further, selling products close to their expiry date is another practice widely implemented by companies:

> *When the product is about to expire, it is offered at a reduced price [...] On the expiry day, the product, if it is still unsold, is placed on a special display, and the customer can buy it at a 50% discount. (Firm F).*

Furthermore, according to the interviewees, it is also necessary to work on FLW prevention, which can be achieved through various tools, among which I4.0 technologies play a key role. Notably, through blockchain technology, not only companies but also the final consumer can track food products, improving process transparency, sharing information, food safety, and avoiding waste (Spence et al., 2018). Compared to small and medium enterprises (SMEs), large companies manage easily to implement these systems and are more prone to control what happens upstream and downstream the value chain, as highlighted by the following quotes:

> *Regarding food loss and waste reduction, we are implementing a digitised system that allows us to monitor the remaining unsold products, and based on this data, we can recalibrate the reordering system [...] Based on everything that remains unsold, alerts are automatically set to guide the reordering of*

> *goods [...] Thus, simplifying as much as possible, if we have 10 packs of milk expiring today, my order has not been correctly calibrated. Consequently, if we placed an order of 100 bricks the day before, our digitised system automatically drops it to 90, so we won't have those leftovers in the next period. Therefore, we are working with a just in time logic, focusing on big data analytics, reducing waste and promoting the circular economy. (Firm F).*

> *Through digitisation, the Hangzhou plant has implemented a system to track waste in detail, raising awareness of waste reduction among employees in different departments, setting waste KPIs for production lines, and encouraging group members. Approximately 11% fewer food losses produced per ton of product were measured due to this technology implementation. (Firm A).*

> *We have been using blockchain for years for tuna tracking [...] In 2015, we developed a completely digital system with IBM to track tuna. We can tell at any time, for every can of tuna or slice of tuna, all the information about it, from when it was caught to when it arrives on the consumer's table. We also use cloud computing [...] We have our own internal management system allowing us to exchange information internally [...] Therefore, we are used to performing an extreme traceability analysis within the company flow. (Firm G).*

> *Regarding traceability, we use the Total Tracking System, which gives transparency to all stages of pasta production [...] In addition, through the scanning of QR codes affixed to the packaging of our products, the final consumer can track and trace the product and all its information throughout the supply chain [...] When the planting takes place, where the wheat grows, when the harvesting takes place, where the wheat is kept waiting to be processed. (Firm V).*

Furthermore, innovations in this field are mostly related to precision agriculture through IoT applications, which, through cross-analysis of environmental and crop factors, identify crops' water and nutrient needs, saving natural resources (e.g. water and land) and improving crop yields (Kamienski et al., 2019), thus supporting CE goals. This is explained in the following quote:

> *Over the past 10 years, in our company, the investments made in farming tools have been very high [...] We have tried to make the land visible in real-time, thanks to new sensors and the Internet of Things, allowing us to determine the activities to do based on the objective characteristics of the land [...] For example, through these systems, we can figure out where water is needed and where there is not [...] Now we are also implementing a system for livestock farming, where milking is done with robots [...] this is advantageous especially for the food management of the animals, avoiding any wastage. (Firm O).*

As a result, agribusinesses are redesigning their value chain through different digitisation tools and CE practices, allowing FLW prevention and reduction. Notably, most CE initiatives aim to valorise waste once generated, such as processing food by-products in different valorisation channels. On another note, digital technologies primarily aim to prevent the generation of avoidable waste, e.g. implementing blockchain technology for product traceability or automatic reordering interfaces to reduce unsold items.

5.3.3 Internal and external drivers for agri-food sustainability

The interviews revealed that the drive towards sustainability differs depending on the size and context in which a company operates. Generally, larger agribusinesses are a source of mimetic pressure on smaller ones. Indeed, smaller companies often implement practices or actions in order to compete for orders and not to lose their market share (Latif et al., 2020). During interviews, managers of larger companies said that they are a pull for smaller ones:

> *We were the first retailer nationwide to start working on reducing and eliminating antibiotics, an issue on which almost all the other retail chains have then started following us [...] The non-use of antibiotics is becoming widespread, and our company has resulted as a driving force for the rest of the sector. (Firm F).*

Another significant theme that emerged from the analysis is the presence of coercive isomorphism. It is why certain manufacturers have implemented certain practices and technologies. Often this pressure is exerted by customers, who impose sustainability standards on their suppliers to maintain a collaborative relationship (Huq and Stevenson, 2020). Compared to SMEs, large enterprises are more used to imposing certifications for their suppliers to ensure the quality of raw materials and control sustainability standards through specific KPIs. Notably, the managers of larger companies having relationships with clients abroad claim to have introduced such practices because of explicit requests from international clients, where circularity and sustainability had already been heard for many years. The following quotes report these aspects:

> *There are stringent selection criteria for suppliers. They must recognise three key points: human rights, environment and sustainability, and transparency. Especially about the criterion of environmental protection and sustainability, suppliers must take steps to ensure that biodiversity is preserved in all its activities and throughout the supply chain [...] The supplier must adopt good waste management practices, promoting the circular economy and food loss reduction. (Firm A).*

> *I would say that our company has been driven more by the attention of international retailers [...] As early as 2009, they were talking to us about sustainability issues. (Firm G).*

However, coercive pressures arise also form suppliers and government entities, as reported in the following quotes:

> *It all started by the suppliers, who are very environmentally aware [...] In a way, they conditioned us [...] Environmental awareness started many years ago in England, where most supplier companies we work with are located. (Firm E).*

> *The European regulation has made a great change [...] Almost all the regulations on packaging, such as the objective of reducing emissions and waste production, are of European origin [...] For instance, all plastic bottles must now have a cap that remains attached to the bottle [...] Many people do not know that, but it is the result of a European directive. (Firm F).*

Regarding normative isomorphism, organisations adopt practices legitimised by relevant professional groups. In this case, non-governmental organisations (NGOs) such as the International Organisation for Standardization (ISO). As a result, normative pressure leads to following strict guidelines and protocols to get professional certifications, through which companies can communicate their commitment to environmental and social protection, legitimising their own business and improving their brand value (Ab Talib et al., 2016).

> *We no longer use conventional fruit but only organic through a search for sustainable raw materials [...] For example, cocoa, chocolate, and coffee come exclusively from qualified suppliers with UTZ or Fairtrade certifications [...] For four years, we have been 22007 and 220055 certified. These are two high-quality certifications included in the GFSI standard and setting stringent rules regarding foodstuffs' traceability both upstream and downstream [...] Consequently, thanks to the practices implemented, we can trace back to the barn from where a specific bottle of milk arrives. (Firm Q).*

However, according to the interviewees, the role of top management is also an essential element since the vision and positioning in terms of top management sustainability lay the foundation for long-term sustainable development. According to Angelo et al. (2022), the role of organisational factors is essential in achieving sustainable performance, as top management's perception of these issues increases the commitment of the entire organisation. This is highlighted by the following quotes:

> *The push towards sustainability began when the group's CEO changed [...] He believed strongly in sustainability and created an ad hoc department, which did not exist before, to work on these issues. (Firm H).*

> *The sustainable and digital transition was really intended by the company [...] We started long before maybe it could be a bit of a fad; thus, there is really a willingness of ownership to focus on sustainability. (Firm B).*

As a result, according to institutional isomorphism, agribusinesses were subjected to coercive, mimetic, and normative pressures, leading to adopting practices and tools to mitigate the amount of FLW and promoting sustainable development. The intensity of these pressures depends on the size of the companies involved in the value chain. In addition, in line with the Resource-based view, organisational leadership emerged as a relevant factor for the digital and sustainable transition of agri-food firms.

5.3.4 Sustainable practices and technologies' limitations

The analysis highlighted the primary limitations as regards the implementation of CE practices and I4.0 technologies. First, these limitations arise from the high required investments to support the digital and sustainable transition. This is particularly true for the SMEs, as highlighted by the following quotes:

> *We were an old company, so a process reengineering was necessary to enable the sustainable and digital transition [...] For instance, we had to buy energy-efficiency machinery [...] However, for a small company, like ours, with three million in turnover per year, it is very complex to make this kind of investment. (Firm Q).*

> *For small enterprises and the most sceptical, sustainability is seen as only a cost [...] Therefore, it must be explained to them that the sustainable transition also implies an economic return in the medium to long term. (Firm H).*

Along with the issue of significant investments, there is undoubtedly the issue of the skills and resources needed to deal with such a radical change. Indeed, it is not only necessary to buy new energy sources or machinery but also to train staff on sustainability issues and the new technological equipment they need to use. According to Närvänen et al. (2021), technology alone does not change the approach to sustainability, but people must change their routines with the help of new technologies. The issue of training is particularly real for SMEs, including family firms, which relate to the lack of necessary resources and infrastructure. On another note, large enterprises are more prone to train their employees on the new technological advancements. These aspects are synthetised in the following quotes:

> *Every year there is a training course on sustainability for all employees [...] Training is done so that everyone is informed about how the world is changing about these issues and how the company is evolving accordingly, so that they can all be aligned to the same goals […] Recently we have also launched an awareness-raising and training campaign regarding IT tools, with specific courses on cybersecurity. (Firm B).*

> *We are a small family business […] We don't have training programs, but we know how important the sustainability is and we make sure nothing gets wasted. (Firm M).*

The infrastructure problem also affects CE practices, particularly regarding the valorisation of by-products and their transformation into biomethane. Indeed, to date, only a few companies have the appropriate facilities, and often the manufacturing companies are unable to valorise them, especially in some regions of Italy. Multinational and larger companies have an in-house biomethane plant, and in some circumstances, they also manage to valorise municipal waste or from other companies.

> *Knowing how to run a biogas plant is extremely complicated, as well as being very expensive to set up [...] That is why many companies, especially smaller ones like ours, have problems developing and operating their own plant, preferring to rely on external companies to process waste through biodigesters. (Firm O).*

Therefore, the main challenges regarding the sustainable and digital transition, especially for the SMEs, regard a large number of investments to make the agri-food industry up to date and reengineer the processes, as well as the implementation of training programs for the employees to manage the new technologies and infrastructures.

5.4 Discussion of the results

Analysing a heterogeneous sample of agribusinesses, we identified the primary causes generating FLW across the value chain and the key enabling factors for implementing and integrating CE practices and digital technologies throughout the value chain (Table 11), finally highlighting their impact on FLW mitigation (Table 12, Table 13). Notably, our findings align with Bloise (2020), demonstrating that the root causes of FLW lie in the interfaces of the different stages of the supply chain, including that between supplier and manufacturer and between manufacturer and retailer. As a result, best practices are in collaborative processes and information sharing.

Furthermore, in line with previous literature (e.g. Yu, 2008; Marshall et al., 2019), one of the main drivers towards the sustainable and digital transition comes from large enterprise customers, inducing the smaller supplier companies to adopt strict sustainability criteria under coercive pressure. However, such pressure often also comes from supplier to customer, generally when the former is larger. Therefore, agribusinesses are pushed to implement practices and tools to avoid FLW, such as biogas production from unavoidable food waste and the implementation of blockchain technology for food traceability. In addition, governments seem to play a mixed role towards the agri-food sector sustainable transition. Although on the one hand, they discourage FLW mitigation by imposing strict regulations on by-products or expiry dates, on the other hand, in contrast with Huq and Stevenson (2020), they incentivise the adoption of sustainable practices, e.g. by imposing food packaging standards on manufacturers to encourage recycling, as highlighted by the interviews. This leads to the following propositions:

Proposition 1. *The larger the company's size involved in the agri-food supply chain, the higher the coercive pressure on smaller businesses upstream and/or downstream of the value chain towards implementing circular practices and digital technologies to mitigate and prevent food loss and waste.*

Proposition 2. *Governments play a mixed role in the agri-food industry's sustainable transition, imposing overly restrictive regulations that sometimes favour and sometimes discourage the mitigation of food loss and waste.*

In contrast with Maignan et al. (2002) and Walker and Jones (2012), our research results indicate that NGOs are not a significant source of coercive pressure in promoting sustainable supply chain management. This research demonstrates the lack of direct assistance or pressure from NGOs to advance more ethical business practices while highlighting indirect influence by encouraging agribusinesses to adhere to regulations and obtain certifications that ensure strict social, environmental, and economic standards for their products and processes. In line with Prajogo et al. (2012), normative pressure is reflected in the adoption of norms and guidelines proposed by external organisations, which through specific set standards, induce companies to obtain environmental, energy, or quality certifications that then become an instrument of assurance for customers. Therefore, it was discovered that NGOs primarily employed normative pressure, which compelled businesses to adhere to stringent regulations to obtain sustainability certifications, hence increasing company image in the market. This leads to the following proposition:

Proposition 3. *Upstream and downstream of the agri-food value chain, normative pressure from NGOs encourages the development of environmental protection and socioeconomic sustainability initiatives.*

Furthermore, among isomorphic pressures, a minor but still important role is played by mimetic force. In line with previous studies (Park-Poaps and Rees, 2010; Wahga et al., 2018), agribusinesses are used to compete for orders and imitate the virtuous actions of the leader companies in the sector to legitimise their business behaviour. As a result, the following proposition:

Proposition 4. *The larger the company's size in the agri-food supply chain, the higher the mimetic pressure on smaller competitors to adopt sustainable behaviours.*

Finally, consistent with previous studies employing the Resource-based view (e.g. Popovič et al., 2018; Haddad et al., 2019), the collaboration of corporate internal resources, particularly top management, was found to be crucial in improving business performance and supporting a sustainable and digital transition. Indeed, top management demonstrated a vital role in taking a proactive view of environmental issues. In the case of family firms, the analysis of the interviews revealed that thanks to an intergenerational change, the level of education of management has increased in recent years. Consequently, the focus on environmental issues has increased. These aspects lead to the following proposition:

Proposition 5. *The role of top management, which directly translates into increased awareness of all organisation levels, is a key driver for the sustainable and digital transition of the agri-food industry. In particular, the intergenerational succession of family firms leads to the change in corporate strategy and implementation of a corporate mission aligned with sustainability.*

Table 11. External and internal pressures on agribusinesses and their effectiveness

Typology of pressure on agribusinesses	*Size*	*Pressure effectiveness on implementation*
Coercive isomorphism		
Customers	SMEs	Medium
	Large	High
Suppliers	SMEs	Low
	Large	Medium
Governments	-	Medium
Mimetic isomorphism		
Competitors	SMEs	Medium
	Large	High
Normative isomorphism		
Non-governmental organisations	-	High
Employees	-	Low
Internal resource		
Top management	-	High
Employees	-	Low

In line with previous research (e.g. Irani et al., 2018; de Souza et al., 2021), this study highlights that digital technologies can help prevent FLW while increasing profitability. Notably, our findings suggest that such technologies are primarily implemented during agricultural production and manufacturing, thus affecting food loss mitigation (Table 12). In line with Ciccullo et al. (2021), we highlight that proper digital technology management can support agribusinesses in increasing food production with fewer resources, reducing waste and environmental implications and supporting the CE goals. However, our findings also suggest that blockchain technology could impact both FLW, allowing for constant monitoring of the goods along the entire value chain, improving the freshness of food and extending its shelf-life. With blockchain, an immediate check is made to automatically record the exact point at which the product may have undergone unsuitable treatment, intervening promptly and avoiding food spoilage. At the same time, through blockchain-based QR codes for food traceability placed on the food packaging, customers become more aware of what they are buying by accessing real-time information on the provenance, safety, and quality of foodstuffs. This leads to the following propositions:

Proposition 6. *Digital technologies are primarily employed upstream of the supply chain to mitigate food losses and support implementing the circular economy. In addition, blockchain technology can* *also help consumers to make more sustainable purchases and raise their awareness towards food waste reduction.*

However, especially for SMEs, the emerging I4.0 technologies are still challenging to implement compared to CE strategies, whose adoption is much more widespread by agribusinesses. In particular, circular practices are mainly employed during agricultural production and manufacturing, leaving the need to deepen how to mitigate the downstream waste stream (Table 12). This aligns with Ojha et al. (2020), who highlighted that efforts to promote CE practices to reduce FLW are still few implemented at the consumer level. According to Agnusdei et al. (2022), consumers must gain environmental awareness towards their food purchases to take virtuous actions and reduce waste. In this regard, our findings suggest that designing sustainable food packaging and labelling can raise consumer awareness towards environmental issues, and adopting a SFSC can decrease the implications of the aesthetic food standards. This leads to the following propositions:

Proposition 7. *Circular initiatives are primarily employed upstream of the agri-food supply chain. In addition, sustainable packaging with eco-labelling and the short supply chain can reduce the environmental implications of the intermediary stage of the chain and encourage consumers to make more sustainable purchasing choices and increase their awareness towards food waste mitigation.*

Table 12. Impact of digital technologies on food loss and waste mitigation by stage of the value chain

Technologies	***Food loss***		***Food waste***	
(Calenda, 2016; Zhang and Chen, 2020)	Agricultural production	Manufacturing	Distribution and Retail	Households
Collaborative Robots	x			
Additive Manufacturing	*Not implemented*			
Augmented Reality	*Not implemented*			
Simulation	*Not implemented*			
Horizontal/Vertical integration	x	x	x	
Internet of Things	x			
Cloud Computing		x		
Cyber-security		x	x	
Cyber-physical System	*Not implemented*			
Big Data Analytics	x	x	x	
Blockchain	x	x	x	x
Artificial Intelligence	*Not implemented*			

Table 13. Impact of circular economy practices on food loss and waste mitigation by stage of the value chain

Circular strategies *(Zhu et al., 2010; Kirchherr et al., 2017; Reike et al., 2018; Dossa et al., 2020)*	***Food loss***		***Food waste***	
	Agricultural production	Manufacturing	Distribution and Retail	Households
Reuse of resources necessary for production	x	x		
Increased product shelf-life			x	x
Incentivise the purchase of edible food that do not meet aesthetic standards through short supply chain			x	x
Valorisation of food by-products	x	x		
Energy recover/biogas production	x	x		
Reduction of resource consumption	x	x		
Food bank donation		x	x	
Training for employees on environmental issues		x		
Sustainable packaging with eco-labelling		x	x	x
Product and system certifications	x	x	x	

5.5 Conclusions, implications, and future research directions

Future food security is gravely threatened by FLW, which also undercuts efforts to reduce emissions to fulfil climate change commitments. Although agribusinesses have been encouraged to embrace I4.0 technologies and CE practices, little research has been conducted to determine how these tools may be effectively implemented in practice in the agri-food supply chains' daily operations.

As a result, through the theoretical basis of Institutional theory and Resource-based view, this study contributes to the literature by investigating the effectiveness of different external and internal driving factors on CE practices and digital technologies adoption, evaluating their level of implementation and integration in the agri-food industry. In addition, we shed light on the primary causes of FLW by taking an overview of the entire supply chain. Finally, we highlight the impact of the implemented solutions upstream and downstream of the supply chain in terms of food loss and/or food waste mitigation. As a result, this broad framework we propose can aid participation in the I4.0 and CE by conceptualising their antecedents and their impact on FLW, set out as eight propositions.

This study suggests that companies aiming to engage in a digital and sustainable transition must redesign plants, products, and the entire supply chain. Notably, agribusinesses need to build an effective system of skills and knowledge within the company and an external system of synergy and coordination to spread the culture of sustainability to all levels of the company and the entire FSC. It is essential to highlight how implementing such practices is a long-term investment leading to environmental benefits and achieving economic goals. A crucial aspect concerns improving communication and information sharing between the different players of the value chain. This could be achieved through the I4.0 technologies. For instance, through digital platforms, it is possible to receive and analyse sales data in real-time so that production can be optimally aligned with sales. However, the main limitations for implementing CE practices and I4.0 technologies in the agri-food sector arise from the onerous investments required and the significant change in processes that a sustainable transition requires. This problem primarily arises from the perspective of building a digitised supply chain. Along with the issue of significant investments, there is undoubtedly the issue of the skills and resources required to deal with such a radical change. Based on the I4.0 and CE benefits highlighted by this study, policymakers may provide financial support and/or incentives to virtuous agribusinesses that aim to engage with the sustainable and digital transition so that they can, for example, organise training programmes on environmental issues, purchase green technologies and implement circular initiatives.

Although considerable attention was taken throughout the multiple case study research, some areas for improvement must be addressed to lay the foundation for future research. First, we analysed a group of 20 Italian agri-food companies, and it may be worth comparing the results of different geographical settings. Therefore, a future study may investigate and compare various countries to assess significant organisational innovations and practice differences. Furthermore, we could not establish causality because our study was exploratory and qualitative. Future research may use a quantitative survey to validate this study's results and determine the cause-and-effect relationship between the relevant factors. Finally, long-term longitudinal research may also observe the success of circular behaviours and digital technologies over time.

6. Coming out the egg: Assessing the benefits of circular economy strategies in agri-food industry

As highlighted in the previous Chapter, agribusinesses have widely started implementing CE initiatives to offset the harmful environmental consequences of supply chain operations. CE is intended to contribute to the current ecological transition, providing economic advantages and preserving global society for future generations (Santagata et al., 2021). In addition, CE strategies can be applied at different supply chain levels, in product design, manufacturing, transportation, consumption, and disposal (Muscio and Sisto, 2020). Nevertheless, as shown in the systematic and bibliometric assessment of the literature, there is a lack of research comparing the environmental outcomes resulting from the application of different CE practices. Given the importance of quantitively recognise the CE-associated environmental advantages, by using the LCA methodology, the present Chapter aims to answer RQ2 (i.e. *What are the environmental impacts of the intermediate phases of the egg industry supply chain?*) and RQ3 (i.e. *What circular economy strategies can be implemented to reduce the environmental implications of the egg industry supply chain?*) by examining a case study from the Italian egg industry. This sector was chosen as representative of the food industry because it provides a primary foodstuff, addresses sustainability and animal welfare challenges, participates in complex supply and distribution chains, and adapts to changing market needs through innovation. As a result, its importance lies in the ability to reflect and influence the broader dynamics of the agri-food sector. Notably, this analysis highlights the environmental benefits and social implications of initiatives supporting CE. First, this investigation highlights the environmental impact of the intermediate phases of the egg industry supply chain. Both primary and secondary data have been collected. We collected primary data via direct interviews with companies' managers throughout all the study phases. Further, despite various external issues affecting the company decisions, the analysis shows that incorporating CE strategies may deliver demonstrable environmental benefits for the companies. The results of the research are expected to support agri-food companies' managers in the decision-making process, helping them to make more sustainable actions compatible with the economic needs of the organisation. Notably, paying more attention to the suppliers' selection as well as choosing the correct type of packaging are identified as the key drivers to reducing the environmental implications of the egg industry supply chain while also ensuring the improvement of financial performance and the development of local economies.

6.1 Theoretical background

6.1.1 Circular economy applications in the agri-food industry

Before proceeding with the empirical investigation, a comprehensive literature analysis of CE strategies in the agri-food industry was carried out with a particular focus on circularization of egg industry. The increasing awareness of both companies and customers towards environmental sustainability has led to adopt several cultivation techniques to respect the environment and people's health. For instance, reusing treated wastewater for agricultural irrigation (Rufí-Salís et al., 2020; Romeiko, 2019) has shown better outcomes than other procurement options in terms of costs and environmental implications. There are several advantages of employing wastewater treatment plants for agriculture, including the ability to access water, quality control, and the capacity to reuse nutrients in the wastewater even during dry seasons (Lahlou et al., 2021; Libutti et al., 2018). Dorr et al. (2021) used the LCA approach on a farm to quantify the environmental impact of the production of 1 kg of fresh oyster mushrooms. By reducing the negative effects of using resources, mostly recycled and reused, CE practices helped improve environmental performance. Indeed, the CE's guiding principles for food chains include reducing waste and surplus, reusing food, recycling nutrients, and fostering a more diversified and healthy diet and lifestyle (Garnett, 2011).

Despite not being founded on waste reduction, the idea of short supply chains can help minimise food waste and hence support the goals of the CE. The commerce of fresh products, with shorter shelf-life, reduced food miles, moderate packaging usage, flexible package sizes, and possibly more conscious customer behaviour, may reduce waste (Kiss et al., 2019).

Furthermore, biofertilisers made from food waste can reduce pollution and GHG emissions while improving soil conditions (Keng et al., 2020; Porterfield et al., 2020). Soil fertilisation is a crucial step in growing crops because it offers the nutrients that plants need to grow. Composting plants produce green compost rich in organic matter and nutrients, capable of increasing soil fertility by improving its physical-structural and biological properties while adhering to environmental and sanitation standards (Cáceres et al., 2016). In addition, manure management is a key driver of the environmental impacts due to direct and indirect nitrogenous emissions, and associated methane emissions. In this regard, Ershadi et al. (2020) identified different strategies that can be applied in the egg supply chain: the use of mechanical ventilation, bedding systems, ammonia scrubbers, manure scrapers, or belts in chicken housing; the covering and addition of biochar to the dung at the manure storage stage; and the incorporation of manure at the stage of land application. Notably, from the bioconversion side, the black soldier fly Hermetia illucens is recognized as an effective bio converter of organic waste into protein and fat, with the benefit that the larval ash should have characteristics similar to compost. The larvae are thus helpful in encouraging more sustainable management of chicken droppings, significantly reducing their quantity and closing the recovery loop by acquiring high-value products for agricultural uses (Bortolini et al., 2020). Further, Ershadi et al. (2021) used the LCA approach to evaluate and compare different technologies and management strategies used to improve nitrogen use efficiency (NUE) in the egg industry, such as the addition of biochar and manure to the soil and the application of acid scrubbers in chicken barns. The adoption of all techniques together resulted in a 15% increase in NUE compared to the baseline scenario, as well as significant reductions in the potential for eutrophication, acidification, and global warming.

According to Kanani et al. (2020), anaerobic co-digestion, anaerobic mono-digestion (biological technologies), pyrolysis and gasification (thermochemical technologies) are four well-developed technologies for valorisation of food waste and key poultry waste streams. As a result, further possible circular strategies concern installing innovative solutions inside the companies, such as biogas plants (Yu et al., 2020; Lansche et al., 2020) and biomass plants (Sadhukhan et al., 2020; Colley et al., 2020). Biogas is produced through the anaerobic digestion process, where agricultural waste is fermented without oxygen at a regulated temperature (Weiland, 2010). Subsequently, biogas is burned in cogeneration units to generate power and heat (Patrizio et al., 2015). On another note, biomass plants produce energy by burning biodegradable materials, such as greenwood, industrial waste, and agricultural waste (Popp et al., 2014). Consequently, biogas and biomass facilities avoid methane emissions from landfills, which are one of the primary sources of GHG emissions in the waste industry (FAO, 2020), and produce cleaner energy to cover various manufacturing and processing operations. However, food waste could also be leveraged in other innovative ways. Concerning the valorisation of eggshells, in order to combat climate change and the greenhouse effect brought on by excessive use of the earth's energy, recycling eggshell waste can be an effective strategy to create a healthy environment and enhance indoor air quality (Shao and Dong, 2020). Further, according to Cecchi et al. (2019), ceramic food waste powder fillers from egg shells could be mixed with bio-based materials, such as the PLA, increasingly used as material for the food packaging, reducing costs and improving technological properties.

Further, the implementation of photovoltaic plants is another approach to generating bioenergy and enhancing company sustainability (Al-Ansari et al., 2017). In this context, Oldfield et al. (2016) conducted an LCA of four methods for managing food waste and food residues: minimization, composting, anaerobic digestion, and incineration. The study found that reducing food waste is more effective than doing business as usual in reducing the potential for global warming, acidification, and eutrophication. Similarly, Lansche et al. (2020) examined the environmental effects of different cassava producing scenarios using the LCA approach. According to the findings, processing leftovers for anaerobic digestion if the generated biogas is used to create power and heat may lower the environmental effect.

Furthermore, previous studies highlighted that minimising packaging weight (Ponstein et al., 2019) and using biofuels derived from food waste (Escobar & Laibach, 2021) can reduce fossil fuels' dependence and carbon emissions associated with agri-food products' distribution. Indeed, reducing GHG emissions during distribution is possible by using lighter packaging (Amienyo et al., 2014), and agro-biorefinery systems allow food waste to be readily turned into biodiesel, which may be used to power lorries for road transportation (Khounani et al., 2021). Using biodiesel instead of petroleum-based diesel has been shown in various studies to have better environmental performance (González-García et al., 2013), allowing climate change mitigation and reducing fossil fuels' consumption (Lazarevic and Martin, 2016). Through LCA, Schmidt Rivera et al. (2020) evaluated the environmental impact of using spent coffee grounds for biodiesel production rather than their disposal through incineration, landfilling, anaerobic digestion, and composting direct application to land.

Moreover, other potential circular initiatives comprise the use of bio-based (Kakadellis & Harris, 2020) and recycled/recyclable food packaging (Accorsi et al., 2015). Plastic waste generation is a global issue since its accumulation in the environment has disastrous consequences for the planet's ecosystem (Peydayesh et al., 2021). As a result, biobased plastics manufacturing for food packaging, characterised by a lower environmental impact than traditional plastics, has expanded over the last decade and is now expected to be two megatonnes (Mt) per year (Sundqvist-Andberg and Åkerman, 2021). Bioplastics such as PLA and aliphatic copolyesters (PBSA, PBAT) are already commercially available with costs that are increasingly close to those of non-biodegradable plastics of petroleum origin (Wang et al., 2016). Generally, bioplastics can be produced from biomasses such as maize, sugar and potatoes; therefore, waste from the agri-food industry can be used for their production (Bassani et al., 2019). Maga et al. (2019) performed a comparative LCA of nine tray solutions for meat packaging. The results highlighted that the trays made with recycled starting material reduced the environmental impact. Further, another method to reduce the impact of packaging waste is to reuse them (Ponstein et al., 2019; Pauer et al., 2019). According to the European Commission (2018), the reuse rate, i.e. the overall number of uses over the package life cycle, is the most critical metric for packaging reusability. As a result, nowadays, many companies are trying to increase this indicator making their packaging reusable for other purposes, thus extending their life cycle (Cox et al., 2010).

6.1.2 Research objectives

The scientific literature lacks a study investigating, through the LCA approach, the environmental consequences of using green alternatives in different settings and applications of the egg industry supply chain. The growing awareness and implementation of CE principles and environmental consciousness necessitate a holistic assessment method incorporating environmental and social consequences into a single, consistent framework (Genovese et al., 2017). Moreover, there is little evidence of this kind of analysis in the Italian egg market, one of the biggest in Europe, with an average yearly consumption of 189 eggs per resident.

As a result, this empirical research will draw on the abovementioned literature to investigate the environmental effect linked to the egg life cycle, mainly concerning the phases of transportation to the packaging/distribution centre and the packaging used. This study also identifies the initiatives supporting CE that may be implemented to help stakeholders make well-informed choices. This paper provides the environmental profile for the eggs' production when CE techniques are used in the supply chain phases associated with the packaging, inner and outer logistics, and distribution. On the other hand, consumers will benefit from having high-quality and safe goods produced and distributed through more sustainable options.

6.2 Methodology

The main goals of this research article are to assess the impacts of the egg industry supply chain from the environmental sustainability point of view and determine which CE solutions might be used to mitigate such impact. In order to achieve these goals, the LCA methodology was carried out. According to Genovese et al. (2017), LCA allows for a better knowledge of supply chain environmental implications, identifying manufacturing processes linked with high energy consumption, resource depletion, and GHG emissions.

6.2.1 Life cycle assessment

LCA is described as a collection and assessment of a product system's inputs, outputs, and possible environmental consequences throughout its lifecycle (ISO 14044, 2006). Therefore, the LCA final report supports the company in evaluating if its decisions are environmentally friendly (Lake et al., 2015). Moreover, LCA is recognised as an approach that can be integrated with other assessment methods to offer complementary perspectives (Santagata et al., 2020; Ulgiati et al., 2006). Roy et al. (2009) highlight that LCA may be used for (1) comparing different goods, services, and processes, (2) comparing alternative life cycles for a particular product or service, and (3) identifying phases of the life cycle where substantial improvements might be achieved. Traditional LCA techniques begin by defining the study's system boundary based on the research objective and accounting for individual effects evaluation inside that boundary (Genovese et al., 2017). Notably, we followed the principles, framework, requirements, and guidelines reported in ISO 14040 and ISO 14044 to conduct the LCA analysis (Nasir et al., 2017). As a result, we discriminated four different phases: Goal and scope definition, Life cycle inventory (LCI) analysis, Life cycle impact assessment (LCIA), and Life cycle interpretation. In particular, the Goal and scope definition phase deals with identifying the study's aim and purpose, specifying the Functional Unit (FU) adopted in the study, the system boundary, and any assumptions made. The LCI analysis is the stage when information is gathered, and calculations are made to quantify the pertinent inputs and outputs of the system. Therefore, in this stage, it is necessary to retrieve the amount of each material and process needed for the FU. Energy and raw materials consumption, as well as outputs and emissions are all often included in inventory data. During the LCIA step, the data gathered in the preceding phase is transformed into possible environmental impacts. The LCIA aims to provide LCA findings in impact categories that are relevant, intelligible, as well as simple to manage and communicate. The environmental impact can be quantified using various measures on the basis of the LCIA approach used (Muthu, 2014). Notably, according to ISO 14044 (2006), we considered all midpoint impact categories included in the LCIA analysis, such as *GWP100*, measured through the equivalent emissions of carbon dioxide released into the atmosphere, *human toxicity*, calculated based on the potential damage to health by various substances, including CO and PM10, and *acidification*, which mainly considers the equivalent emissions of sulfur dioxide affecting waterways and rains. OpenLCA software version 1.10.3 was used to model the inventory and perform the LCIA. Notably, the CML-IA baseline method was employed to calculate the environmental impact. For instance, considering the *GWP100* impact category, the cumulative impacts of emissions were depicted using kg CO_2-eq linked to the unit input over 100 years. The total emissions of the good's supply chains were calculated by multiplying these values by the emissions amount per unit given from the ecoinvent database. The ecoinvent allocation default database was employed for all of the data in this investigation. Finally, the Life cycle interpretation is a systematic process for identifying, qualifying, checking, and assessing the outcomes from the LCA's first three stages, also offering ideas for improving the environmental performance. In addition, we performed Scenario analysis, i.e., identifying and assessing potential future events or scenarios to forecast different possible outcomes. In particular, starting from the literature review presented in the above section, we first identified potential solutions to be implemented in the egg industry to reduce the environmental implications of the supply chain. Subsequently, Scenario analysis allowed us to model different CE strategies and find the potentially beneficial solution for the environment, in terms of environmental impact reduction, through an evaluation with the support of computer software. As a result, Figure 11 highlights our LCA study's framework.

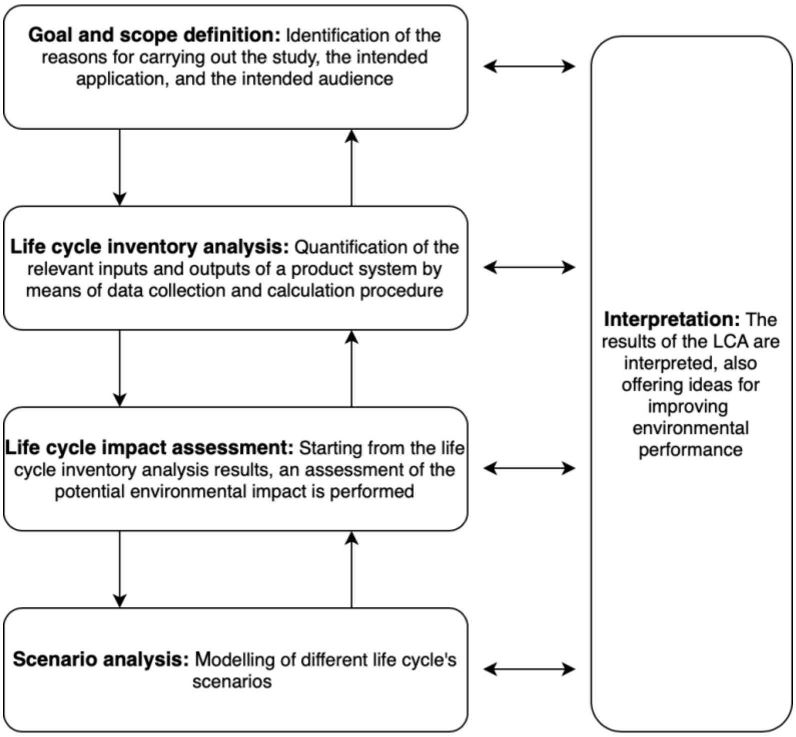


Figure 11. LCA framework adapted by ISO 14040 (2006)

Furthermore, this study employs a *gate-to-gate* analysis, considering the intermediate phases of the supply chain, starting from the eggs' procurement and raw materials production, including the packaging process up to supermarkets' distribution. The system boundary is set based on the study's objectives to allow for individual impact evaluations inside the system, as shown in Figure 12.

The LCA's FU measures the examined system's function and operates as a basis of reference for the inputs and outputs. The FU is described as a product system's performance metrics used as a reference unit in a LCA study, according to ISO 14040 (2006). In this study, the FU comprises 6 medium sized extra-fresh barn eggs, the packaging, and the labels.

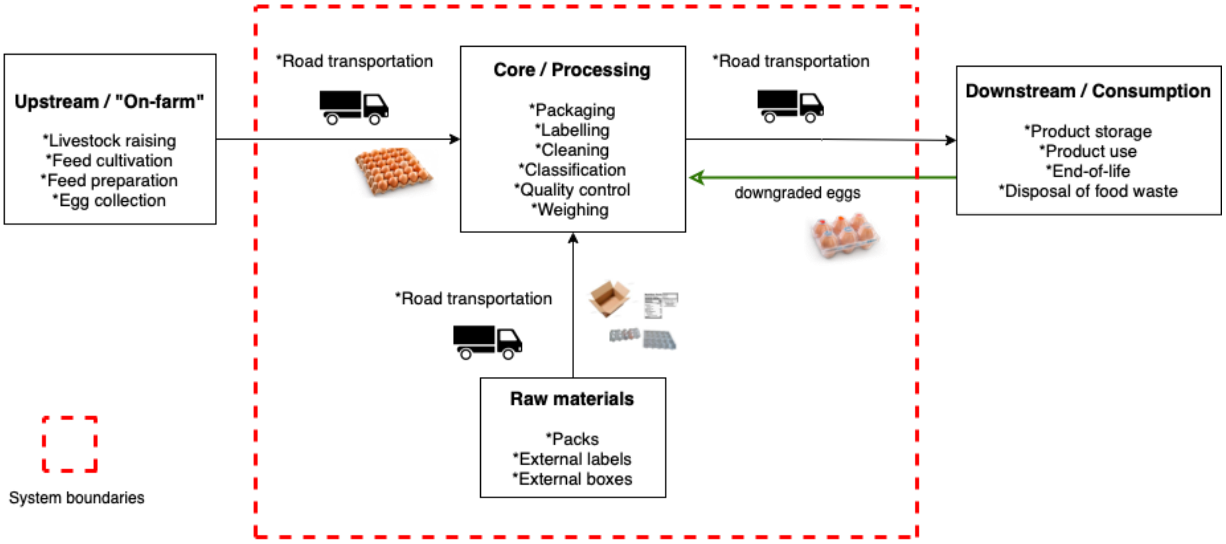


Figure 12. System boundaries for current study

6.2.2 Case study

This paper presents a case study on the environmental impact of an egg company in southern Italy. For privacy reasons, the commercial name of the firm will not be revealed. The entire production chain of the company examined is subjected to strict control rules implemented in several stages on every element of the supply chain: from raw materials to breeding, from laying of eggs to collection, from selection to computerized control of production in the warehouse, packaging, and distribution at points of sale. All the required supply chain data has been gathered from company interviews and is complemented with secondary data retrieved from the ecoinvent database (Nasir et al., 2017). This web-based database contains detailed LCI data (Wiedmann et al., 2011).

6.2.3 Data collection

Primary and secondary sources were used to collect LCI data which was subsequently used to assess the environmental impacts. The primary data was gathered through face-to-face interviews, corporate documents and websites, and emails, while the ecoinvent 3.1 database was used to get secondary data. Five company employees (i.e., CEO, marketing manager, production area responsible, sales area responsible, and the quality department responsible) were interviewed to collect information about all the processes of the company (e.g., procurements, materials used, and the distribution phase). Furthermore, the ecoinvent database has been used as the provider of the background processes to calculate the inventory using real-world data, leading to a more accurate assessment (Stavropoulos et al., 2016). In particular, we asked for the following information: (1) the type and weight of the eggs; (2) the type and weight of the materials used for packaging; (3) the distance and means of transport employed in the supply chain for the materials' delivery; (4) the amount of energy used for production.

6.2.4 Improvement phase

The quantitative analysis based on LCA was successively reinforced by face-to-face interviews with the company's managers. The primary purpose of the interviews was to analyse the possible circular solutions to be adopted in the company, evaluating their environmental impact, costs, and potential advantages. For this improvement phase, we focused on the GWP100 impact category, which is one of the primary categories for quantifying the environmental impact, according to the Intergovernmental Panel on Climate Change (IPCC) (Dadhich et al., 2015). GWP100 incorporates several greenhouse gases, such as CO_2, CH_4, and N_2O, based on their individual 100-year global warming potential (Somers and Quinn, 2019). Therefore, we aimed to provide suggestions for reducing the carbon dioxide emissions of the most critical phases of modelled egg supply chain, highlighted in sub-section 6.3.2. The GWP100 values were chosen as an environmental indicator because of the high impact of the food industry on climate change and because they are a reliable measure used in LCA research (Clune et al., 2017). According to Clark et al. (2020), about 33% of global GHG emissions are related to how food is produced, transported, and consumed: researchers estimate that global food produces 16 billion tons of CO_2 per year between 2012 and 2017. This system that feeds more than seven billion people could lead Earth to exceed the two-degree global temperature increase threshold that the signatory countries of the 2015 Paris Agreement pledged not to exceed (Clark et al., 2020). This explains why many food LCA studies employ the GWP100 as the only impact category. For example, 92% of Australian food LCA studies reported GHG emissions (Renouf and Fujita-Fimas, 2013).

Some possible interventions for reducing CO_2 emissions concern the installation of photovoltaic plants (Corcelli et al., 2019), as well as biogas and biomass plants (Lansche et al., 2020; Gaglio et al., 2019), in order to cover the energy needs for eggs packaging. More recently, biogas plants have been employed in egg farms to treat FLW, avoiding harmful GHG emissions into the environment and producing green heat and energy (Kanani et al., 2020). In addition, other farms have effectively incorporated solar projects to reduce energy costs and enhance environmental performance. Other possible interventions regard the use of eco-friendly packaging (Sundqvist-Andberg and Åkerman, 2021; Kakadellis & Harris, 2020; Accorsi et al., 2014). Different firms have stopped using packaging in PET, thus proposing new biodegradable and recyclable ones. Notably, Furthermore, the depletion of limited natural resources, such as water, requires a more urgent system for global sustainability (Dora et al., 2021), and many agri-food firms have started to reuse wastewater in the production phase. Finally, it is highlighted that incorporating local suppliers into the design process can increase the company's environmental, social, and economic performance (Allais et al., 2015). Regarding this aspect, the scientific literature provides controversial results. Some studies revealed that the means of transportation matters equally as much as the distance (Coley et al., 2011) and that the distance food is transported is not the key food sustainability determinant (Pelletier, 2017; Farmery et al., 2015). This is particularly true when the volume of resources/products and the efficiency and specificity of logistic operations are considered. In these cases, territorial-specific factors (urban/rural areas, consumer preferences, producers-consumers relationships) (Kiss et al., 2019) or supply chain infrastructure (Majewski et al., 2020) can play a relevant role. However, short food supply networks are generally seen as more environmentally friendly than large-scale food distribution systems due to lower GHG emissions (Aguiar et al., 2018; Tudisca et al., 2015). Reduced CO_2 emissions, reduction of FWL, and less packaging use may be achieved via shorter FSCs, which minimise food miles. i.e. the distances between the site of production and consumption (Kiss et al., 2019). Past studies on the egg industries have revealed that a low environmental impact could be achieved by reducing the distance of transport (e.g. Dekker et al., 2013). Notably, a short supply chain is characterised by a restricted number of economic operators devoted to collaboration, local economic development, and tight geographical and social relationships between producers, processors, and consumers (European Rural Development Regulation, 2015). Developing a local economy makes it possible to revalue the traditions and the link with the territory while also contributing to food safety (Kiss et al., 2019). Indeed, by purchasing directly from the producer, it is possible to check the production methods, seasonality, and the absence of chemicals and fertilisers, ensuring food quality and increasing consumer awareness of sustainability issues, which leads to less food waste (Raftowicz et al., 2020). As a result, buying local goods is a mindset that is intrinsically tied to sustainability and the growth of a sustainable economy and society. Therefore, the benefits of adopting a short supply chain are (1) waste reduction and less environmental impact, (2) support for the local economy, and (3) small-scale trade and effective logistics (Kiss et al., 2019). For this reason, many businesses pick local suppliers to get eggs “Km 0”, enhancing the resources at a territorial or proximity level to reduce the environmental consequences of transport and create a local identity of the product. In addition, as also highlighted in the results of the multiple case study analysis presented in the previous Chapter, *sustainable packaging with eco-labelling and the short supply chain can reduce the environmental implications of the intermediary stage of the chain and encourage consumers to make more sustainable purchasing choices and increase their awareness towards food waste mitigation (Proposition 7).* Our study confirmed that using sustainable packaging materials can not only reduce dependence on non-renewable resources, helping to preserve natural resources for future generations, but can also improve brand image and consumer confidence. Similarly, the short supply chain reduces the consumption of resources, such as fuel and water needed to transport and store food products, as well as the number of intermediaries between producer and final consumer, allowing for greater freshness and quality of food products and positively influencing the consumer's perception of the overall quality of the product.

6.3 Data analysis

This section reports the preliminary findings of the study, thus highlighting the data concerning the different eggs' quality offered by the company, packaging raw materials, transportation modes, and electricity consumption. Subsequently, the environmental implications of the current company's supply chain are shown.

6.3.1 Preliminary findings

The company offers eggs classified into three different categories: quality class, rearing class, and weight class (Table 14). Notably, the quality class depends on the intended use and comprises Class A and Class B eggs. Class A includes two sub-categories: the fresh eggs (intended for direct consumption) and the extra-fresh eggs (packaged and delivered at the supermarket on the same day of production); Class B eggs, called “second quality,” are intended exclusively for the food industry.
The rearing class is divided into four categories: organic eggs, free-range eggs, barn eggs, and laying cage eggs. The organic eggs come from organic farms where the hens are raised outdoors, on land covered by vegetation, cultivated with organic methods, and fed exclusively with feed from organic farming. The free-range eggs are produced in open-air farms where the hens live in total freedom, in wide-open spaces of vegetation and covered shelters. The barn eggs come from barn farming, where the hens are free to scratch in a covered environment and within which they can move freely but without access to the outside and can lay their eggs in the nests. The laying cage eggs production comes from high production plants, subjected to constant technological renewal to ensure authenticity, freshness, and total quality in the trade and consumer services.

Regarding the weight class and according to current legislation (Commission Regulation, 2008), the eggs should be categorised by weight as follows: XL - very large (weight of 73 g or more); L - large (weight between 63 g and 73 g); M - medium (weight equal to or between 53 g and 63 g); S - small (weight less than 53 g). The average weight for the fresh and extra-fresh eggs of all the rearing categories is about 320g for a pack of 6 medium eggs, about 380g for the 6 large eggs, and about 440g for the 6 extra-large eggs. As mentioned above, we focused on extra-fresh barn eggs weighing 61g for the case study, as highlighted in Table 14. Different reasons justified this choice. First, the extra-fresh barn eggs' sale represents the company's core business since the most significant percentage of the firm's revenues comes from this eggs category. Second, according to European Commission (2017), even if cage farming is at the top of the ranking (44.9%), in recent years, the interest in barn farming has been increasing, reaching 35.6% of the total EU laying hens farming, followed by free-range (12.8%) and organic farming (6.6%).

Furthermore, supply chain management of extra-fresh eggs is more complex than the other categories, thus requiring great attention from the environmental perspective. By law (Commission Regulation, 2008), eggs are considered extra-fresh until the ninth day following the laying date. Therefore, eggs must be recalled from supermarket shelves and the wording "Extra" removed after that date. This is the case of downgrading eggs from the extra-fresh class to the fresh class. The packages of extra fresh eggs not sold must be collected from the supermarket and sent back to the company, which replaces the extra fresh product daily or at the latest three times a week to ensure the availability of a fresh product in the shops. The extra-fresh eggs that must be downgraded, return to the company to be relabelled with the wording “Fresh”. The eggs must not be re-packed, so they do not undergo any further packaging, but the outer label is adjusted and remain in the initial packaging process. It follows that the relabelling process implies more consumption of packaging materials compared to the other egg categories. Further, after the egg packs have been relabelled, the company redistributes products only to certain supermarkets. Consequently, due to the complexity of the supply chain, characterised by more kilometers of transport and continuous delays, the company's managers stated that the most polluting egg category is the extra-fresh, thus expressing interest in reducing the environmental impact of this specific good.

Table 14. Category of eggs.

Quality class	**Class A** (intended for direct consumption)	Fresh eggs **Extra-fresh eggs**
	Class B (intended for the food industry)	
Weight Class	Small (weight < 53g) **Medium (53g < weight < 63g)** Large (63g < weight < 73g) Very Large (weight > 73g)	
Rearing Class	Organic eggs Free-range eggs **Barn eggs** Laying Cage eggs	

Note: in bold underlined, we have highlighted the product chosen as the unit of analysis

Regarding the suppliers of eggs, they provide both the quality categories of eggs. The distances between the farms and the company, for each category of rearing, are identified as follow: for the cage eggs, there are two suppliers, one located at 649 Km of distance and one at 791 Km; for the barn eggs, those considered in the analysis, suppliers are distant from the company 747 Km and 682 Km; for the organic eggs, there is one supplier situated at 659 Km.

Each eggs' supplier delivers the goods with a lorry of 15.5 tons, Euro 5. In 90% of cases, the vehicle shall be in fully laden conditions.

For the packaging suppliers, there are the suppliers of packs, external labels, and external boxes. The providers of packs are two: one gives Polystyrene (PS6) packs and one Polyethylene terephthalate (PET1) packs. The first is located 685km far from the client company, while the second is 1364 Km. The single PS6 packs weigh 12.5g, whereas PET1 packs weigh 18g. The supplier uses lorry > 35 tons, Euro 5 to deliver the freight. The packaging of the extra-fresh eggs is always made with PS6 while for the fresh barn eggs, the package made with Polyethylene terephthalate is employed and, for the other fresh categories of eggs, interchangeably packs made of PET1 or PS6 are used. Instead, the external labels are made of non-corrugated fiberboard (paperboard, PAP21), and they singularly weigh 15g. The manufacturer of these items is situated 659km from the company, and they are shipped by 28 tons lorry, Euro 4. The external boxes, made with corrugated fiberboard (PAP20), are provided by suppliers 35km away from the company, and a lorry of 28 tons, Euro 5, was used. A single box weighs 390g, and it contains 24 packs of 6 eggs.

Concerning the phase of eggs distribution, the vehicles used are 3.5 tons lorry, Euro 6. Further, only one sales point is considered for the analysis, located 38 km from the company.

Finally, according to data supplied by the manufacturing area responsible, the average electricity consumption within the company for the packaging phase, net of the energy produced by the photovoltaic system, is approximately 0.0948 kWh.

A synthesis of the quantitative data collected for the analysis is reported in Table 15. Notably, we started from the processes representative from Europe (RER), and then we changed the electricity grid mix for the Italian specific context. The national average mixes were developed using Italian statistical data for provincial egg sector activity volumes and Italian provincial electricity mixes as available in the ecoinvent database. This was done because egg supply chain activities are not evenly distributed between provinces and because each province has distinctive electricity grid mixes.

Table 15. Life cycle inventory for the functional unit production

Category	Input	Quantity	Unit	Emission Intensity (Kg CO_2-eq/unit)	Emissions (Kg CO_2-eq)
Materials	polystyrene (PS6), general purpose, RER	0.0125	Kg	3.6624	4.578E-2
	corrugated board box (PAP20), RER	0.01625	Kg	1.0025	4.578E-2
	folding boxboard/chipboard (PAP21), RER	0.0300	Kg	1.0560	3.168E-2
	polylactide, granulate (PLA)	0.0125	Kg	3.1528	3.941E-2
Transport	transport, freight, lorry 16-32 metric ton, EURO4, RER	9.8850	Kg*Km	1.689E-4	1.67E-3
	transport, freight, lorry 16-32 metric ton, EURO5, RER	0.56875	Kg*Km	1.705E-4	9.699E-5
	transport, freight, lorry 3.5-7.5 metric ton, EURO6, RER	46.7115	Kg*Km	5.258E-4	2.456E-2
	transport, freight, lorry 7.5-16 metric ton, EURO5, RER	273.402	Kg*Km	2.2E-4	6.02E-2
	transport, freight, lorry >32 metric ton, EURO5, RER	8.5625	Kg*Km	8.526E-5	7.3E-4
Electricity	electricity, high voltage, IT	0.3414	MJ	0.1836	6.269E-2

6.3.2 Environmental impacts

Implementing the methodology discussed in section 6.2, Figure 13 highlights the environmental impact relative to the current supply chain of the company, mainly concerning the packaging and transportation phases. It is interesting to investigate which processes contribute the most to overall environmental impact once the results of the LCIA have been determined. In particular, the analysis highlights that the phases with the highest environmental impact for almost all impact categories are energy consumption and the transportation of eggs to the company.

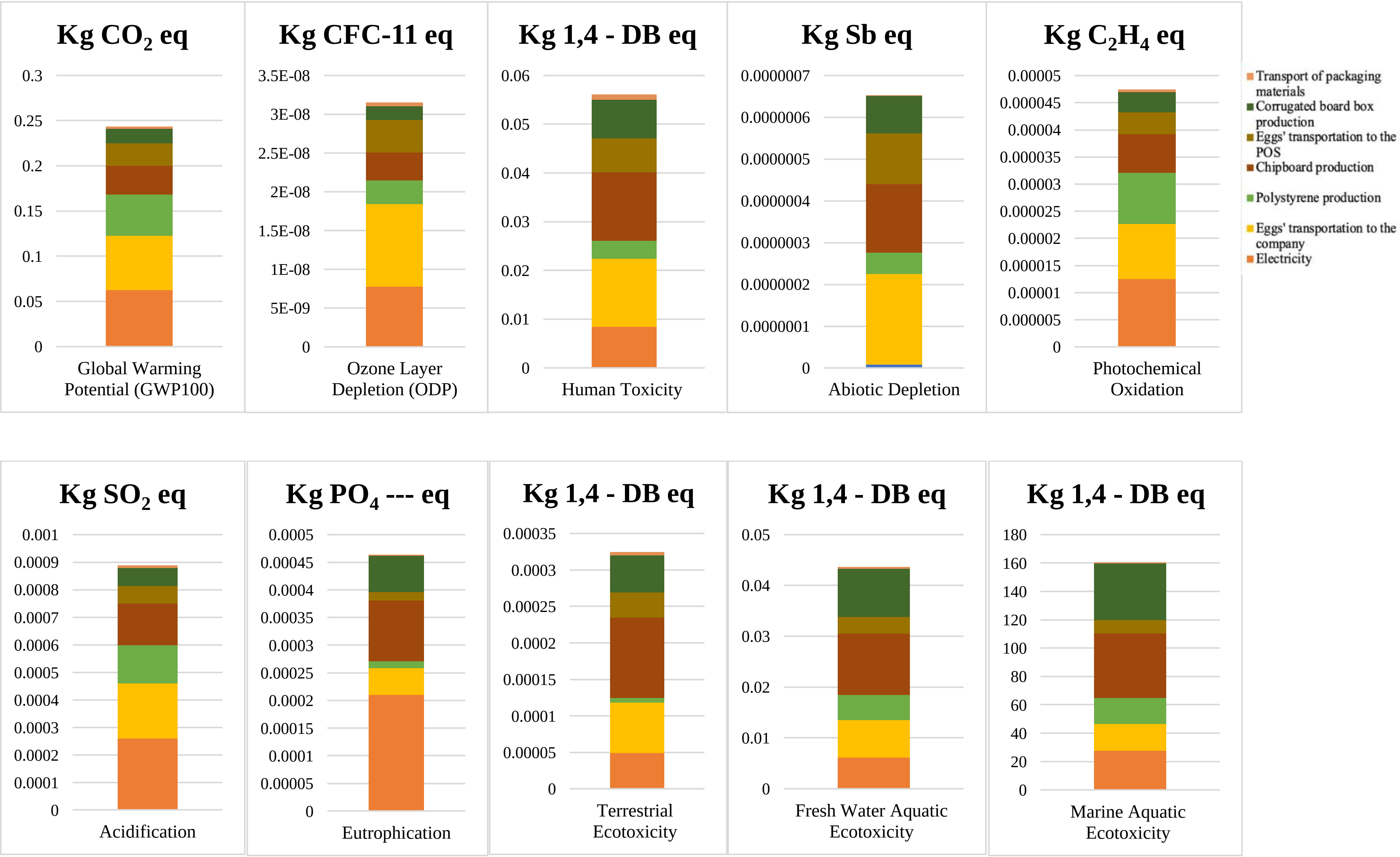


Figure 13. Environmental impact of the modelled egg supply chain, across all impact categories

Notably, Figure 14 illustrates the breakdown of carbon emissions hotspots of the present supply chain in terms of kilograms of carbon dioxide equivalent (Kg CO_2-eq), considering the two eggs' suppliers S1 and S2 separately, located 747 km and 682 km far from the company, respectively. Indeed, S1 and S2 differ only in the transport process. Table 16 highlights the exact values of the contribution analysis. The overall environmental impact related to the first supplier (0.2437 Kg CO_2-eq) is 2% higher than the second one (0.2385 Kg CO_2-eq) due to more kilometres of transport. Looking at the breakdown of Kg CO_2-eq (Figure 14), the stacked bar graphs highlight that, for both S1 and S2, electricity consumption, eggs' transportation to the company, and polystyrene production are the main hotspots (about 2/3 of the total impact). Notably, for S1 and S2, eggs transportation contributes to approximately 25% and 23% of total emissions, respectively. Instead, the electricity consumption contributes to about 26%, and the material produced for the packaging is about 19% for both S1 and S2.

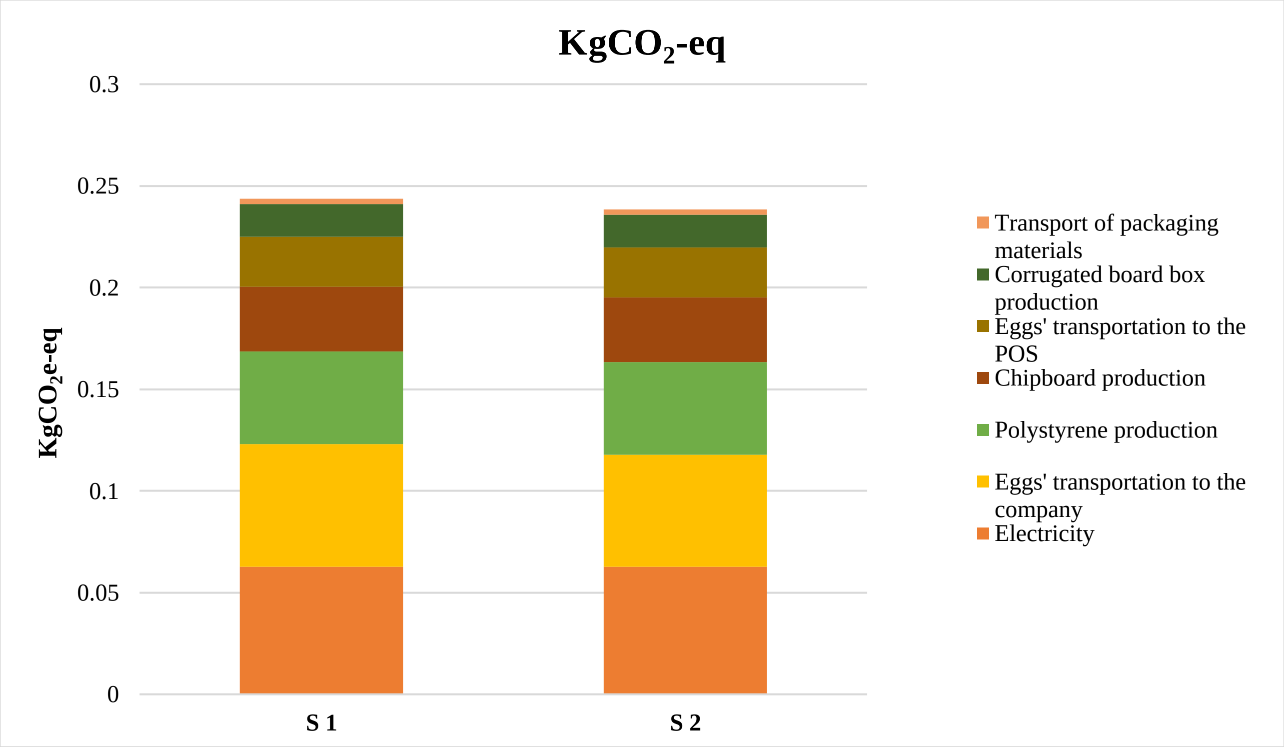


Figure 14. Breakdown of carbon emissions hotspots

Table 16. Analysis of carbon emissions contribution

Supply chain stage	Carbon emissions ($KgCO_2$-eq)
Electricity	0.06269
Eggs' transportation to the company	0.05496
Polystyrene production	0.04578
Chipboard production	0.03168

Eggs' transportation to the POS	0.02456
Corrugated board box production	0.01629
Transport of packaging materials	0.002495

6.3.3 Semi-structured interviews

Five face-to-face semi-structured interviews with the company's managers have been conducted to evaluate which practices can be implemented to reduce carbon emissions. Notably, the literature review results presented in this chapter were triangulated with those of the multiple case study analysis presented in the previous one to identify different potential interventions. We also consulted data found on egg companies' websites and reports to have a broader overview of possible strategies to be implemented. From the interviews, the company examined is in line with other firms for energy recovery and renewable sources. Notably, the company already has a photovoltaic system that produces a part of the energy requirement; therefore, in the short term, the company will not consider implementing additional plants such as biogas and biomass. The managers were in favour of promoting a SFSC and supporting the local economy. In addition, the interviewees pointed out that, in the past, the company had already used plastic-free cardboard packaging, but it involved a decrease in sales because the product was not visible from the package, which was non-transparent. Thus, consumers could not be sure of the conformity and integrity of the eggs. As a result of a discussion with the interviewees, it has emerged that the feasible strategies were the selection of a local egg supplier, which must be as close as possible to the company, thus favouring the “Km 0” and a SFSC, and the choice of a transparent bio-based packaging. Bioplastics share the characteristic of being biodegradable and compostable, i.e. they guarantee their certified organic recyclability in different environments (Jem and Tan, 2020). In CE, every waste must be reintroduced into the cycle through recycling. In this sense, bioplastic packaging can play a fundamental role: it quickly becomes a valuable and natural resource, such as fertilizer for the soil, closing the virtuous circle. Further, organic waste or waste products from the agri-food industry can be used as biomass for microbial fermentation and therefore for bioplastics production (Bassani et al., 2019). In addition, packaging must comply with current food safety regulations and overcome the market issues raised from previous experience, ensuring information transparency and protecting the final customer.

Furthermore, the company specified that suppliers' selection must be strictly related not only to price and distance but also to animal welfare. The new supplier will have to own sustainability and quality certifications guaranteeing compliance with the regulations on how animals are raised, ensuring, for instance, that the chickens are nourished only with a feed with the correct nutrient supply. As a result, the interviewees revealed that animal welfare is a key element included in the decision-making process of the company, especially in relation to consumers' health, aiming to achieve social sustainability objectives, such as food and nutritional safety.

6.4 Discussion of the results

In this section, by employing LCA, the two different scenarios identified for reducing the environmental implications of the egg industry supply chain are evaluated: the selection of a new supplier and the choice of bio-based packaging.

6.4.1 Scenario 1: Supplier Selection

Focusing on the eggs' transport from the rearing to the company and looking at the strategies of CE used in the competitors' plant emerges the absence of a local supplier. This action is already applied in some previous studies. If the distance of supplier increases or decreases, it would affect all the analysed systems similarly, thus local suppliers should be used wherever possible (Oliver-Solà et al., 2009). Therefore, some research to identify a supplier so-called “Km 0” has been done. After careful investigation, no supplier has been identified in the same region of the company examined to satisfy its needs and the required quality standards, including respect for animal welfare. Notably, the European Commission has established several marketing standards concerning the quality and freshness of the eggs, food safety and hygiene, transport rules, and the egg-washing systems (Commission Regulation, 2008). In addition, the company requires from its suppliers the utmost care for the environment and respect for the welfare of animals, providing them with all the necessary care and leaving them the freedom to live in an environment suited to their needs, where they can shelter and rest. The majority of the companies meeting the above parameters are located in different regions of central-northern Italy. As a result, we have selected a supplier “near Km 0”, located 154 Km from the company, in an adjacent region. The chosen supplier is a farm that falls within the above-mentioned quality parameters. As shown in Figure 15, the amount of the total GHG emissions is 0.02456 kg CO_2-eq for the new supplier (S3), instead of 0.0602 kg CO_2-eq and 0.05496 Kg CO_2-eq, respectively, for S1 and S2. Consequently, S3 reduces the Kg CO_2-eq by 59.20% and 55.31% compared to S1 and S2, respectively. As a result, it is suggested to prefer a "near Km 0" supplier, if not possible at "Km 0".

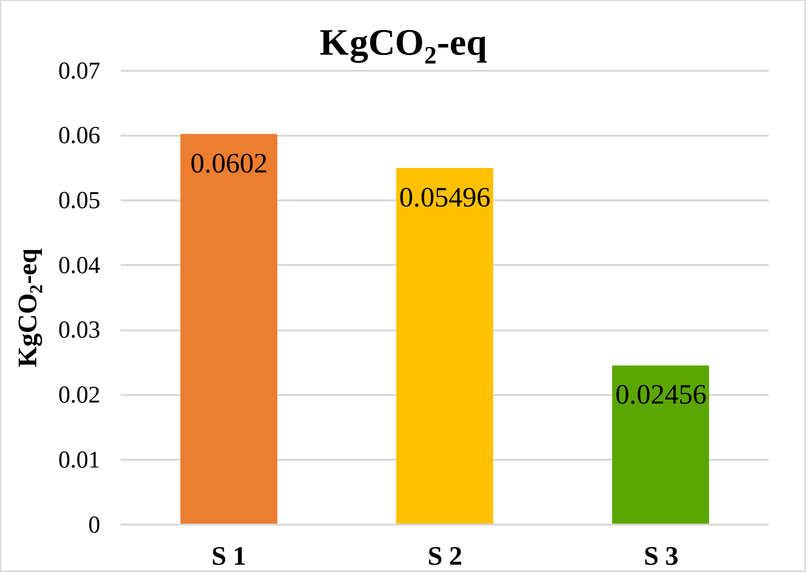


Figure 15. Direct contributions from egg transportation processes to GHG emissions

6.4.2 Scenario 2: Bio-based packaging

Circular supply chains' benefits for the environment may be examined in relation to the packaging employed. Sustainable and biodegradable packaging will be the ideal candidate material to replace plastics and extend the shelf life of foodstuff (Ma et al., 2022). The research of the perfect packaging is complex because food packaging and its functionality must comply with governmental requirements and standards related to materials in contact with foodstuff (Kochańska et al., 2021). Egg marketing standards are governed by Commission Regulation (2008), which specifies that packs must be shock-resistant, dry, clean, and in excellent repair, as well as made of materials that protect the eggs from odour and quality deterioration, since the primary role of packaging is protecting against breakage, theft and bacterial contamination. Therefore, an alternative sustainable packaging compliant with current regulations is PAP 21. The "PAP" symbol distinguishes the materials made up of recyclable, biodegradable, and compostable cellulose fibers, and "21" identifies the type (i.e. non-corrugated fiberboard or paperboard). However, paperboard material was not considered due to negative feedback from the company. As discussed in sub-section 6.3.3, the company has already used a similar material in the past, resulting in poor sales performance because of the packaging non-transparency. The use of transparent, bio-based, and biodegradable plastics such as polylactic acid, also known as polylactide or PLA, can be a sustainable solution to solve this problem. There is evidence of previous studies successfully adopting it because it complies with food safety regulations and has good packaging properties (e.g. Suwanmanee et al., 2013). This material is an innovative bioplastic produced from renewable-sugar-based materials such as corn, sugarcane, or cassava (Smith, 2005). Therefore, from a CE perspective, agri-food wastes can be used as biomass for microbial fermentation for producing PLA (Bassani et al., 2019). This recyclable material has the same characteristics of polypropylene (PP), polyethylene terephthalate (PET), and polystyrene (PS): it is transparent, polished and has great strength characteristics, and has good properties for food packaging applications. Biodegradability is a key benefit of adopting PLA for packaging. PLA is an eco-friendly material to use in packaging because of the ecologically friendly manufacturing method and the raw resources it uses. PLA can be recycled of in two primary methods. According to Lim et al. (2008), the first is compost degradation: when a PLA product is used for the first 180 days of its life, it is entirely biodegradable and may be composted. Within seven days at 60°C and under damp conditions, PLA decomposes into digestible polymer fragments. It will become soil amender and fertilizers, and the waste will turn into a useful and natural resource, thus promoting CE. The second is renewable energy recovery through incineration (Castro-Aguirre et al., 2016). Indeed, since PLA does not contain any chlorine atoms, it may be appropriately burnt under regulated circumstances without forming dioxins (highly toxic chemicals).

Therefore, we have checked the packaging supplier website in order to retrieve the list of materials used for production. Among these materials, we also identified PLA. As a result, in our LCA model, the PS6 material has been changed by the new PLA material, considering the same weight and the same supplier. Examining the contribution of the packaging production processes involved in the analysis, Figure 16 highlights a decrease of the total emissions from 0.04578 Kg CO_2-eq related to the PS6 production to 0.03941 Kg CO_2-eq linked to the PLA production, with an overall reduction of about 14%.

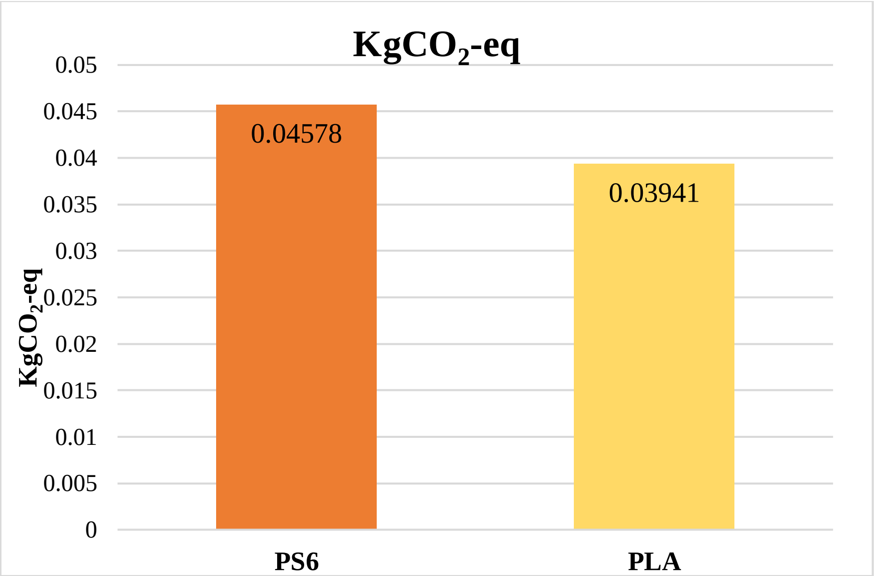


Figure 16. Direct process contributions of the current material and the PLA in terms of GHG emissions

6.4.3 Scenario 3: Adoption of both Km0 supplier and Bio-based packaging

Therefore, by analysing the entire egg supply chain, choosing eggs' suppliers “near Km 0” and bio-based and biodegradable plastics as packaging materials, the overall environmental impact in terms of total emissions is 0.1895 Kg CO_2-eq. Consequently, there is a reduction of total emissions of 22.24% compared to selecting S1 and using PS6, and a reduction of 20.54% compared to selecting S2 and using PS6 (Figure 17).

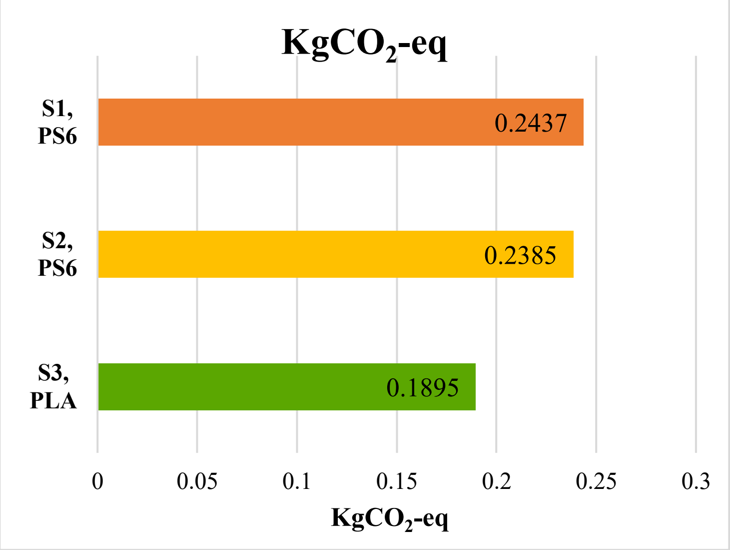


Figure 17. Comparative analysis of the CO_2 emissions of different supply chain configurations

6.5 Uncertainty analysis

Parameter uncertainty (i.e. uncertainty in inventory data) is the most often examined source of uncertainty in LCA research. Notably, stochastic modelling, most typically Monte Carlo (MC) simulation, is generally used to carry out these analyses (Bamber et al., 2020). MC approach essentially entails performing numerous assessments with random input values selected from a certain probability range. The variability of the assessment's output may then be used to determine the effect of this input uncertainty (Raynolds et al., 1999). In this study, using the ecoinvent data quality system in openLCA, a pedigree matrix was employed to evaluate uncertainty associated with stochastic variability and data quality. All foreground and background systems LCI data points were given pedigree scores. Then, openLCA software was used to perform 1000 MC simulation runs to evaluate uncertainties for the LCIA results (standard error). Each input variable's value was randomly chosen throughout each run from a predetermined distribution for this variable. The final model outcome was the mean values and standard deviation of the GWP100 impact category, measured through Kg CO_2-eq.

The uncertainty analysis results are shown in Table 17. Notably, the difference between the baseline and the alternative scenarios (adoption of both local supplier and bio-based packaging) was statistically significant ($p < 0.05$) for the chosen environmental impact category.

Table 17. Monte Carlo simulation (1000 runs) results for the production of 1 packs of eggs, including baseline and alternative scenarios

	Mean	**SD**	**5% Percentile**	**95% Percentile**	**Median**	**Standard Error**	***P*- value**
Climate change – GWP100 (kg CO$_2$-eq)							
Baseline scenario	27.17	263.68	-74.73	110.40	-2.25	7.20	0.00
Adoption of both local supplier and bio-based packaging	-1.62	46.16	-42.12	58.44	-1.59	1.26	

6.6 Further opportunities

Three additional options from the researchers' field analytical analysis are addressed below to offer a complete picture of the case study under consideration. As a result, these opportunities represent critical areas that should be addressed in future investigations.

The company should search for new opportunities and solutions available in the market to improve the vehicle's fuel efficiency (McKinnon, 2006). For example, the vehicles used to transport the final product to the point of sale could be replaced with plug-in hybrid vehicles, rechargeable using the energy produced by the photovoltaic plant. This solution involves an initial investment that will yield potential long-term environmental benefits (Graham-Rowe et al., 2012).

Furthermore, another critical point comes from the external boxes used two/three times and then go in the waste separation. Thus, reusable and washable boxes could replace them to have a longer life cycle. It is demonstrated that if reusable ones replace single-use packaging, the carbon emissions would potentially be lower (Camps-Posino et al., 2021).

Finally, the possibility of implementing a more closed-loop supply chain via recycling food waste may be investigated. The valorisation of agri-food by-products is an effective strategy for implementing the CE in the agri-food industry (Gebremikael et al., 2020). As a result, valorisations of wastes of eggs dismissed from the machine during the processing stage can transform the eggs rejected into products of higher value, such as pet food or soil compost.

6.7 Conclusions, implications, and future research directions

Scholars argue that a significant transition from traditional production and consumption paradigms to creative, sustainable, and cleaner development models that are both environmentally friendly and beneficial to society's growth is required (Sen, 2010). In this regard, the CE can be considered a critical factor in achieving climate-neutral (Mazur-Wierzbicka, 2021), as well as a fair and inclusive economy (European Commission, 2021c). There is a great need to build a worldwide transition to a fair/just CE for everyone, providing environmental preservation and a sustainable pathway of human growth (Padilla-Rivera et al., 2020; Schröder et al., 2020; Clausen and Gyimóthy, 2016).

The LCA methodology is a reliable basis for quantifying the environmental implications of a product's life cycle and defining actions aimed at sustainable production and consumption. Notably, LCA studies should be executed in four steps: definition of the goal and scope of the study, LCI analysis, LCIA, and life cycle interpretation and improvement (ISO 14040, 2006; ISO 14044, 2006). The LCA approach was used in this research to assess the environmental implications of the egg industry supply chain. The functional unit was set as 6 extra-fresh barn eggs packed in a medium size. OpenLCA software was used to conduct the analysis. Data for the evaluation were provided from an egg company in southern Italy and are supplemented with secondary data from the ecoinvent database. The processes included in the analysis started from the procurement of raw material, including the packaging process, up to supermarket distribution. In the first part of our analysis, we considered all midpoint impact categories included in the LCIA phase. Subsequently, in the Interpretation and Improvement phases, some actions, starting from scientific literature and market analysis of competitors in the same market segment, have been identified as potential solutions to optimise the environmental performance of the processes considered in terms of carbon emissions reduction. Focusing on the processes that have the greatest impacts in terms of carbon dioxide emissions: (a) the contribution of electricity has not to be improved because the company already has a photovoltaic plant that produces some of the required energy to cover the needs for the processing phase; (b) the contribution of kg CO_2-eq due to the transport of eggs from rearing to the company in analysis can be improved by choosing local suppliers, so at km 0, or, if it is not possible, near km 0; and (c) a significant contribution comes from the material used for the packaging and a great alternative, which matched the environmental impacts performance and the requirements of the company to have a transparent packaging, is the biodegradable, compostable material, such as the PLA.

This work provides estimates of the GHG emissions when CE strategies are applied in the egg supply chain. Agri-food companies' managers should pay more attention to selecting the supplier and choosing the type of packaging, which are the key drivers of the environmental implications in the distribution of the eggs. The results show how a complete change in the agri-food production and distribution system, focusing on local production, can improve environmental performance (Coelho et al., 2018), and how using natural and biodegradability resources, such as the PLA, can be an excellent option to adopt an eco-friendly approach to packaging for eggs industry.

Furthermore, companies' managers should use the environmental product declaration as a strategic tool to disseminate the environmental communication of products and services. Indeed, using the LCA analysis results, the environmental impacts associated with the product's life cycle, such as CO_2 emissions reduction, could be made explicit on product labels and packaging, attracting consumers' attention, and pushing them to buy sustainable labelled products. The environmental product declaration provides certified data on the environmental performance of goods and services. It is a fundamental aspect for organisations that wish to differentiate themselves from the competition by communicating detailed information on the environmental impact of their products to allow more informed purchasing choices.

Regarding the social sustainability dimension, the choice of a SFSC might help revitalise local communities: the value and significance of the product, as well as its origin, inspire pride, social cohesiveness, and a feeling of belonging to a particular location and community (Malak-Rawlikowska et al., 2019). In conclusion, the SFSC can enhance the development of the local economy while also guaranteeing food safety and reducing food miles and the overall social and environmental impacts.

As an integral part of the food chain, the egg industry involves several stages, from hen rearing and egg production to distribution and retailing. This complex network of activities reflects the general dynamics of the food industry in terms of production, transportation, and marketing, requiring great attention to numerous aspects, including product quality, food safety, food security, sustainability, and responsiveness to market needs (Kleyn and Ciacciariello, 2021). Therefore, the results of this study can be generalised beyond this specific sector to the broader agri-food domain. Different criteria, including responsible management of natural resources, GHG emissions mitigation, and food miles reduction, may be adapted and applied to other segments of the agri-food sector, reducing the overall environmental implications of the industry.

One of the study's shortcomings is its reliance on secondary data for conducting the process LCA study. In addition, the study's conventional LCA technique has a weakness. The problem of the limited system boundary must be addressed to improve the effectiveness of the environmental impact assessment. As a result, a *cradle-to-grave* analysis of the egg supply chain is essential for the agri-food industry in future research. Indeed, considering the entire egg life cycle, contributions from egg processing could be small relative to the contributions from egg production systems due to feeding and manure management processes (Ershadi et al., 2021; Pelletier, 2017). Future studies could also perform complete LCAs as regarding improvement strategies, thus increasing the depth of the analysis and revealing potential trade-offs in environmental impacts between different improvement scenarios. Further, the future investigation could evaluate and compare the environmental implications of different egg categories, such as barn eggs, those selected for this case study, and organic eggs, particularly important for sustainable development in the agri-food sector. Indeed, organic eggs are produced by hens fed grain that has been cultivated organically without the use of pesticides and chemicals. In addition, future investigation could use a system expansion or an allocation approach for dealing with co-products, i.e. class B eggs, which have not been taken into consideration in our study. Future research could also investigate the environmental impact of the egg supply chain in further geographic settings to highlight similarities and differences with the Italian industry. Finally, future studies could discuss the economic implications, as they are often the most challenging aspect of implementing CE programs. Thus, the LCA method could be integrated with a) the LCC technique, analysing the most efficient response from an environmental perspective and an economic one, and b) the S-LCA technique to examine the product or service social and sociological components, as well as its actual and expected positive and negative consequences throughout its life cycle. Notably, through the LCC analysis, it is possible to evaluate all the product life cycle costs, constantly referring to a specific functional unit, and finally calculating the added value. Conducting an LCC analysis of a product/service helps predict the costs companies must incur to market a new product, from pre-production to its disposal. Environmental LCA and LCC are complemented by S-LCA, which uses both general and site-specific data and may be quantitative, semi-quantitative, or qualitative. By employing the S-LCA analysis, it is possible to determine the social impact of the entire supply chain under investigation through a series of indicators, such as the number of serious accidents and the working conditions. As a result, according to the Triple Bottom Line framework (Elkington, 1998), integrating LCA, LCC, and S-LCA analyses will close the loop by considering all three pillars of sustainability. As a result, the future investigation should compare the environmental/social impacts with the economic outcomes, thus evaluating the optimal trade-off solution, improving the decision-making process and the overall industry's performance.

7. Understanding the determinants of food waste reduction: An exploratory study using structural equation modelling

Once we determined the key technologies and practices leading to improving agribusinesses' environmental performance, our final objective was to focus on the last link in the food chain, i.e. the consumer, and test the influence of such tools on consumers' attitudes and intentions not to waste food. The household level is the value chain phase where food is thrown most frequently (Gaiani et al., 2018). Households' food waste is a significant obstacle to sustainable development since it directly impacts the consumer economy, depletes natural resources, and generates GHG emissions (FAO, 2020). As a result, determining the factors mitigating consumers' food waste is essential to protect our ecosystem and improve the quality of life. The global community confronts a significant challenge in providing secure food for approximately 9.1 billion individuals by 2050 (Abdelradi, 2018), and the United Nations' 2030 Agenda and its SDGs seek to abolish hunger and malnutrition as well as ensure sustainable production and consumption practices by 2030 (Duro et al., 2020). Based on the above grounds, we decided to focus on the consumption stage and investigate consumers' sustainable behaviour relating to food waste and the factors contributing to its mitigation. Through the multiple case study analysis, we revealed that the SFSC, blockchain technology for traceability of foodstuffs, and sustainable food labelling and packaging could help consumers make more sustainable purchases and raise their awareness towards food waste reduction. However, the qualitative nature of the case study cannot establish causality. Therefore, using the TPB, this Chapter aims to answer RQ5 (i.e. *What circular economy practices and technological innovations adopted by agribusinesses exert influence on consumers' behavioural intention concerning food waste reduction?*) by conducting a statistical survey on a sample of 283 Italian food consumers. The analysis based on partial least square–structural equation modelling (PLS-SEM) demonstrated that consumers are more willing to buy sustainable packaged food items by enhancing labelling systems to incorporate more practical sustainability information and QR codes for product traceability. In turn, by purchasing sustainably packaged foodstuffs and relying on TPB, attitudes can be increased to strengthen intentions not to waste edible food. This research provides meaningful implications for the agri-food sector. First, in order to support a more sustainable production and consumption model, businesses will be able to benefit from the major factors influencing consumer behaviour regarding food waste mitigation, including environmentally friendly packaging, sustainable labelling, and blockchain-based tools for food tracking. In the same way, by leveraging these practices and technologies, companies can increase their market share by offering goods that consumers are more willing to purchase. In addition, by shedding light on the pushing elements influencing sustainable consumer behaviour regarding foodstuffs, policymakers for sustainable food consumption should promote better educational campaigns to support the achievement of SDGs 2 and 12. Notably, in order to encourage sustainable consumer behaviour, the connection between sustainable packaging and food waste reduction should be recognised by relevant parties in the value chain, including consumers, food producers, manufacturers, retailers, and regulators of packaging legislation.

7.1 Theoretical background

7.1.1 Theory of planned behaviour and food waste literature

TPB is the most employed theory in social psychology for explaining and forecasting human behaviour (Ajzen, 1991; Soorani and Ahmadvand, 2019). Terlau and Hirsch (2015) state that consumer behaviour is one of the most unpredictable and unstable components of the whole value chain; practical strategies to change consumer behaviour in favour of sustainable consumption are very difficult to implement. The analysis conducted by Janssens et al. (2019) shows that purchasing behaviour is the primary driver of food waste, and have bought more food than required is often a source of food waste. Furthermore, the relationship between planning behaviour and food waste is moderated by the intention to prevent food waste. Siraj et al. (2022) state that, in order to encourage sustainable consumer behaviour, policymakers and marketers must increase consumer awareness about sustainable labels and their positive environmental implications. The results examined through structural equation modelling conducted by Soorani and Ahmadvand (2019) demonstrate that attitude, subjective norm, and guilt are all predictors of the intention to mitigate household food waste. The problem of food waste in households is addressed by different studies (e.g. Visschers et al., 2016; Abu Hatab et al., 2022), pointing out that interventions should concentrate on enhancing consumers' perceptions of their own behavioural control to reduce food waste in households. In contrast, Schmidt (2019) investigates how well consumers manage to avoid wasting food by abstaining from practices like eating past-expiration food. Vermeir and Verbeke (2008) highlight that public policy and marketing must be carried out to stimulate sustainable food consumption among consumers. Other studies (Lorenz-Walther et al., 2019; Amato et al., 2021) investigate out-of-home settings (in university canteens), concluding that reduced portion sizes are needed to make a contribution towards food waste reduction. The results from the analysis of Graham-Rowe et al. (2015) demonstrate the usefulness of applying an extended TPB model to predict motivation and behaviour in reducing household waste of fruits and vegetables. In contrast, von Kameke and Fischer (2018) investigate the use of planned food purchasing plans to reduce household food waste. The research conducted by De Canio and Martinelli (2021) shows that consumers are prepared to pay a premium price for sustainable foods with an EU quality label. The survey results of Aitken et al. (2020) propose that with the integration of more practical information into the labelling system, including the products' health, environmental, and societal benefits, consumers' perceived behavioural control will be amplified, leading to the intention to buy organic products. In addition, the research conducted by Ogorevc et al. (2020) focuses on organic foods. Consumers are increasingly accepting regionally-made food products as well as organic goods; in fact, they are viewed as genuine, high-quality food items that support environmentally-friendly production and consumption practices. Prakash and Pathak (2017) investigate the impact of sustainable packaging on consumer purchase intention. The study's findings support the notion that customer willingness to pay, as well as personal norms, attitudes, and concerns about the environment have a significant impact on purchase intentions for environmentally friendly packaging.

7.1.2 Research objectives

The consumer behaviour literature on household food waste reveals several theoretical and methodological gaps. From the analysis of the papers, there is a dearth of research investigating factors that influence consumers at the food purchasing stage, which may then influence their attitude and intention towards reducing food waste. This stage could lead to unsustainable behaviours, purchasing food items not consumed and thrown away, and thus inappropriate household food waste. Thus, from this thorough analysis, companies in the FSC can take cues and understand what to intervene on, thus also aiming to downsize production systems by applying technologies and practices of sustainability and CE. Indeed, the research question aims to investigate what factors influence consumers' food purchasing choices and the impact they have on consumers' intentions to minimise food waste.

7.2 Construction definition and hypotheses development

The theory behind this research is the TPB, a cognitive theory developed by Icek Ajzen in 1991 to predict human behaviour (Ajzen, 1991). This theory hypothesises that an individual choice to perform a certain behaviour can be predicted by his or her intention to employ it. The motivational factors that affect behaviour are believed to be captured by intentions, which highlights how eager people are to try and how much effort they plan to put into engaging in the behaviour. Further, according to the TPB, behaviour is most effectively predicted by intention, which also has a significant impact on behavioural performance. The intention is determined by three factors: attitude towards a behaviour, subjective norms, and the individual's perceived behavioural control (Aitken et al., 2020). This theory has been used extensively to forecast consumer behaviour intentions across a wide range, including food consumption (Chun T'ing et al., 2021), sustainable and ethical (Lorenz-Walther et al., 2019), and organic food behaviours (Chu, 2018). TPB provides a basis for exploring emerging consumer behaviour and has also demonstrated the ability to be flexible and easily adaptable when analysing the further role of concepts not present in the original model (Mondéjar-Jiménez et al., 2016). Ajzen (1991) believes that TPB can include outside predictors and its fundamental variables if there is sufficient proof of them effectively capturing significant variation in behavioural intention (Siraj et al., 2022). Further, TPB investigates the drivers of consumer behaviour in the context of social commerce, including purchase intention (Sadeli et al., 2023). As a result, TPB has been used in many research areas, including agriculture, and has produced reliable hypotheses and outcomes. Notably, TPB has frequently been used in the agri-food sector with noteworthy outcomes (Wenzig and Gruchmann, 2018). The majority of these studies focused on healthy food categories, such as fruits and vegetables, organic food, and, more lately, plant-based foods (Sogari et al., 2023). This research used TPB to examine consumer intention towards reducing food waste.

7.2.1 Traceability

Foodstuff traceability is defined in Regulation (CE) 178/2002, reported on the Ministry of Health website, as "the ability to trace and follow the path of a food, feed, food-producing animal or substance intended or likely to be incorporated into a food or feed through all stages of production, processing, and distribution." It follows that traceability is a crucial safety tool for the agri-food value chain. Indeed, according to recent literature, with an efficient traceability system along the entire FSC, consumers' trust concerning the anticipated credibility attributes will materialise, and the agri-food industry's competitive advantage will be established (Pappa et al., 2018). Italian consumers have a greater incentive to trust the traceability system's effectiveness. When information regarding traceable food is certified, consumers may have confidence in the accuracy of the information provided about the food's manufacturing process and provenance (Menozzi et al., 2015). Consumers' lack of knowledge about traceable food products could be viewed as a barrier to developing the traceable food industry (Lin and Wu, 2021). QR codes are the perfect tool for providing customers with traceability information without increasing packaging material, thus contributing to environmental sustainability. Today, QR codes with traceability labels have been increasingly adopted and placed on food packaging, making it simpler for consumers to obtain traceability information (Spence et al., 2018). According to some studies, consumers are more likely to trust products if they believe the traceability information is of high quality, and the propensity to purchase them increases (Cavite et al., 2022). The hypothesis being formulated is as follows:

H$_1$. Knowledge of foodstuffs traceability positively influences the proneness to look for sustainably packaged food items.

7.2.2 Sustainable labelling

Food labelling is the main point of contact between the manufacturer and the final consumer. It reports the details that consumers analyse during purchasing to help them decide whether to buy or not that particular product. Broader, clearer, more targeted, and more credible labelling could contribute to consumer decision-making and greater dissemination of information, including information regarding the sustainability of products and packaging (Aitken et al., 2020). Communicating the use of eco-friendly packaging can improve brand image and consumer confidence. Several research investigations have revealed a positive relationship between eco-labels and environmentally conscious purchases (e.g. Alam et al., 2023). A trustworthy labelling system that can enlighten consumers regarding the product's environmental impact will help them make more environmentally friendly food choices (Stranieri et al., 2023). The practical use of sustainability labels in purchase decisions relies not only on customers' motivation and awareness of sustainability but also on their familiarity with, prior utilisation, and trust in the relevant certifications and labels (Hinkes and Christoph-Schulz, 2020). The hypothesis assumed is as follows:

H_2. Sustainable food labelling positively influences the proneness to look for sustainably packaged foods.

7.2.3 Local food supply

Consumer interest in local production has been increasing in recent times. Consumers typically place a premium on quality, authenticity, ethical standards, the nation of origin, and sustainable food production. Local foodstuffs are increasingly preferred by consumers; these products are perceived as authentic, high-quality goods, contributing to sustainable production and consumption systems development (De Canio and Martinelli, 2021). Therefore, consumers of local food products are more willing to buy less beautiful items, perhaps because they are distinctive and perceived to be healthier (Hempel and Hamm, 2016). The quality and health of the products, economic and social benefits, and ecological sustainability are the three main factors that influence whether or not people choose to purchase and consume local goods (Peral-Peral et al., 2022). The scientific literature lacks a commonly accepted definition of local food (Wenzig and Gruchmann, 2018). However, there are some designations, such as agricultural products and foodstuffs with a Protected Designation of Origin (PDO) label are those whose quality or characteristics are primarily attributable to a specific geographic environment and are grown, processed, and prepared in that location. On the other hand, the Protected Geographical Indication (PGI) label designates agricultural goods that are closely related to a specific geographical area. Based on their geographic origin, these goods have a certain quality, reputation, or other specific characteristics (European Commission, 2004; Likoudis et al., 2016). The SFSC focuses on the development of the territory and decreases the implications of the aesthetic food standards; as a result, it could be critical in influencing consumers' attitudes regarding purchasing choices, thus helping to lessen food waste. The accompanying research hypothesis follows as a result:

H_3. The proneness to look for local food products positively influences the attitude towards purchasing from responsible enterprises.

7.2.4 Sustainable packaging

Today, the concept of sustainability is increasingly on the rise among manufacturers, retailers, and consumers. Recycling issues appear to be a particularly hot topic for consumers, who are increasingly motivated to contribute to sustainable development, particularly regarding environmental protection. Companies' green policies are becoming more aware of the food packaging materials' environmental impact, and consumers are increasingly sensitive and conscious of the presence of recyclable and compostable packaging in their food purchasing choices (De Canio and Martinelli, 2021). Consumers favour packaged goods with environmentally-friendly features compared to non-recyclable plastic packaging (Prakash and Pathak, 2017). It follows that consumers expect a responsible company to provide sustainably packaged food products (Honkanen et al., 2006). In addition, according to Brennan et al. (2021), food packaging assists in minimising households' food waste by increasing food products' shelf-life, coming in a variety of sizes for households, and providing instructions on how to use and store foodstuffs. Therefore, sustainable food packaging is intended to communicate its features to the consumer, enabling trust towards the food product, as well as material reuse and waste reduction (Nguyen et al., 2020). Brennan et al. (2021) state that consumers' perception towards the role of sustainable packaging in mitigating food waste needs to be further investigated. Indeed, the critical role of packaging and its use as a tool for communication can influence the change in consumer attitudes towards the purchase and consumption of foodstuffs. Notably, packaging can influence how consumers assess products before deciding to buy, elicit strong reactions, and push consumers to specific purchasing choices (Nguyen et al., 2019). The lack of, insufficient, or incomplete information on the packaging of food items influence consumers' perceptions and the ability to change their behaviours (Aitken et al., 2020). Based on this, the following hypotheses are formulated:

H_4. The proneness to look for sustainably packaged food products positively influences the attitude towards purchasing from responsible enterprises.

H_5. The proneness to look for sustainably packaged food products positively influences perceived behavioural control over having plate leftovers.

7.2.5 Attitude towards responsible enterprises and Intention towards food waste reduction

Based on supporting literature, this research conceptualised a framework using an extended version of TPB. The attitude variable towards purchasing from responsible enterprises corresponds to the TPB attitude variable, defined as each person's favourable or unfavourable evaluation of a given behaviour. Consumer intention towards food waste reduction (engage in sustainable behaviour), which corresponds to the intention variable of TPB, as this theory predicts the intention to engage in a given behaviour related to a given problem, was identified as the research model variable (Aktas et al., 2018). The goal is to promote sustainable consumer behaviour aimed at reducing food waste. It has been discovered that consumers feel guilty about wasting food and are worried when they do so (Visschers et al., 2016). Attitude positively influences intention to reduce food waste (Aktas et al., 2018), which in turns influences food waste reduction behaviour (Thompson et al., 2020). Recent literature highlighted that attitude might positively influence the intention to minimise different kinds of food waste, such as fruits and vegetables (Coşkun and Yetkin Özbük, 2020). The hypothesis related to this variable is as follows:

H_6. Attitude towards purchasing from responsible enterprises positively influences consumer intention towards food waste reduction.

7.2.6 Perceived behavioural control

Perceived behavioural control describes the perceived simplicity or complexity of acting in a certain way (Ajzen, 1991). Therefore, the beliefs that underlie the perceived behavioural control include the resources and capacities of the individuals for engaging in a certain conduct as well as the perceived difficulty in carrying out that behaviour (Siraj et al., 2022). Theoretically, people are more likely to engage in a behaviour if they have greater influence over it (Cavite et al., 2022). Previous studies on responsible consumption demonstrate a significant positive relationship between perceived behavioural control and people's behavioural intentions (e.g. Hassan et al., 2016; Moser, 2016; Huang et al., 2018). In particular, different empirical studies demonstrated the positive effect of perceived behavioural control on intention and behaviours for reducing food waste (e.g. Lorenz et al., 2017;

Coşkun and Özbük, 2020). Similarly, perceived behavioural control has been employed to investigate a variety of pro-environmental activities, and its significant effect on intention has been established (e.g. Botetzagias et al., 2015; Wan et al., 2017; Govindan et al., 2022). As a result, we propose the following hypothesis:

H7. Perceived behavioural control over having plate leftovers positively influences consumer intention towards food waste reduction.

Based on these assumptions, the research model is displayed in Figure 18.

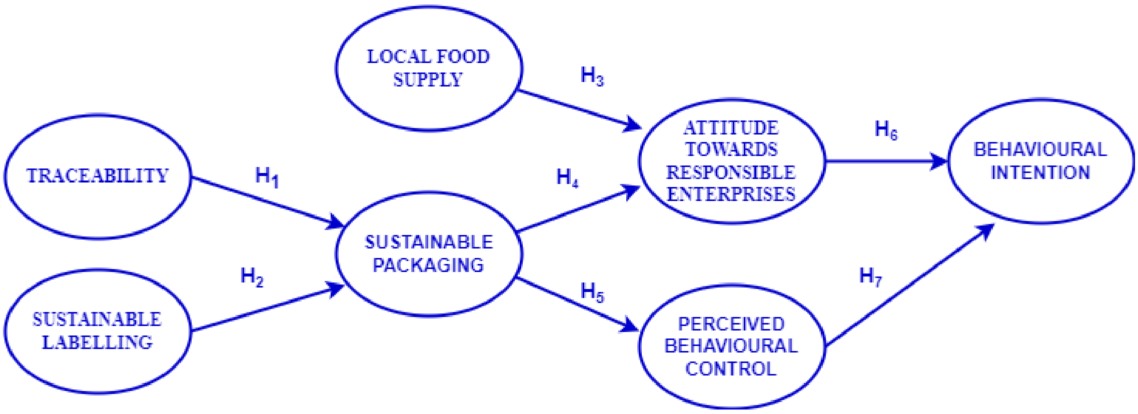


Figure 18. Research model

7.3 Materials and Methods

The research model was tested through the partial least squares - structural equation modelling (PLS-SEM) method. When there is an exploratory nature to the relationship between the dependent and independent variables, PLS-SEM is more appropriate than CB-SEM (Gupta et al., 2020). This approach is well known for its capacity to predict outcomes in success factor studies and is an excellent way to concurrently estimate complex interrelationships (Ken Kwong-Kay Wong, 2019).

7.3.1 Data collection

From July to September 2022, a sample of 337 Italian consumers took part in the research. Survey research, which is the most common and practical methodology for data gathering, was used to acquire the data (e.g. Lin and Guan, 2021; Chu, 2018). The questionnaire was conducted online, and 337 responses were collected; excluding incomplete and incorrect responses, 283 were usable. A semi-structured questionnaire, divided into 33 items with 14 questions, was sent to participants to identify and bring out their intentions towards reducing food waste and investigate the importance and knowledge of the factors identified and considered important during the food purchasing stage. The questionnaire was structured into three sections. Questions about the interviewees and their household sociodemographic profiles are included in the first section, as reported in Table 2. Section 2 includes questions aimed at analysing consumers' attitudes towards purchasing from responsible enterprises and intentions towards food waste reduction. Finally, section 3 regards food purchasing habits regarding sustainable labelling, sustainable packaging, local food supply, and knowledge of foodstuffs traceability.

The objective is to study whether the identified factors can influence consumers' attitude towards purchasing from responsible enterprises and perceived behavioural control over having plate leftovers, and their impact on intention towards reducing food waste. On a 5-point Likert scale, with categories ranging from Completely disagree (1) to Completely agree (5), respondents were asked to indicate their degree of agreement with the statements (relative items of each variable), with the exception of the questions related to the local food supply variable, where the category used ranges from Never (1) to Always (5). The reference sample for the study appears to be fairly homogeneous (Restrepo, 2022). The majority of the people who responded to the questionnaire are aged between 21 and 40 years old. There is a good distribution between females and males. It should be clarified that the smallest possible sample size, according to Hair et al. (2012), must be 10 times the highest number of internal or external links in the PLS model. In the case under consideration, the maximum number of linkages concerns the latent variable of sustainable labelling, which has 7 indicators. There are 283 total valid answers in this instance; consequently, the prerequisite for PLS-SEM analysis is satisfied (Hair et al., 2012). Therefore, it is feasible to claim that the sample of 283 respondents is a sufficient number for using the PLS-SEM methodology (Hair et al., 2012). Table 18 depicts the summary of the sample profile.

Table 18. Demographic measurements

Demographic measurements	Percentage (%)	Frequency
Age		
0-20	3.5%	10
21-40	80.6%	228
41-66	12.4%	35
67 +	3.5%	10
Gender		
Male	39.2%	111
Female	60.0%	170
Prefer not to answer	0.8%	2

Education level		
Elementary school	0.7%	2
Secondary school	26.5%	75
Bachelor's degree	53.4%	151
Postgraduate (Master's, Postgraduate, Doctorate)	19.4%	55
Number of household members		
1 person	3.5%	10
2 people	13.1%	37
3 people	27.2%	77
4 people or more	56.2%	159
Number of children in the family (up to 18 years old)		
No children	55.1%	156
1 child	16.3%	46
2 children	20.5%	58
3 children or more	8.1%	23
Marital status		
Single	78.8%	223
Married	15.9%	45
Widowed	0.7%	2
Divorced	4.6%	13
Net monthly household income (€)		
Less than 1000	6.0%	17
Between 1000 and 2000	34.6%	98
Between 2001 and 3000	28.6%	81
Between 3001 and 4000	15.2%	43
Greater than 4000	15.6%	44

7.3.2 Measures

Each latent variable in the model was measured by a set of indicators extracted from the supporting literature. In particular, for the Attitude towards purchasing from responsible enterprises variable, the items are five and were taken from Bianchi et al. (2021). For the Perceived behavioural control variable, the items are three and were taken from Lorentz-Walther et al. (2019). For the Behavioural intention towards food waste reduction variable, the items are five and were taken from Mondéjar-Jiménez et al. (2016) and Janssens et al. (2019). For the Sustainable packaging variable, there are four items that were extracted from Prakash and Pathak (2017) and De Canio and Martinelli (2021). For the Sustainable labelling variable, there are seven items, extracted from Aitken et al. (2020) and Hinkes and Christoph-Schulz (2020). For the Local food supply variable, there are four items, taken from Żakowska-Biemans et al. (2019), Likoudis et al. (2016), and Hempel and Hamm (2016). Finally, the five items of the Traceability variable were taken from Cavite et al. (2022). Details of the constructs and related items associated with the variables are given in Table 19.

Table 19. Variables with relative references

	VARIABLES AND ITEMS	**REFERENCES**
	SUSTAINABLE PACKAGING	(Prakash and Pathak, 2017), (De Canio and Martinelli, 2021)
SP1	• I make every effort to buy packaged products made from recycled materials.	
SP2	• Whenever possible, I buy products packaged with reusable or recyclable containers**.**	
SP3	• I am willing to pay more for food products with sustainable packaging.	
SP4	• When I buy food product with sustainable packaging, I feel like I have done something positive for environment.	
	SUSTAINABLE LABELLING	(Aitken et al., 2020), (Hinkes and Christoph-Schulz, 2020)
SL1	• Most sustainable food products are clearly labelled, so I can figure out whether they are sustainable or not from the packaging.	
SL2	• When shopping I can easily distinguish between sustainable and non-sustainable food products.	
SL3	• Through clear labelling, it is easy to identify sustainable food products.	
SL4	• I trust the information on sustainable product labels.	
SL5	• I am confident I understand the information on sustainable product labelling.	
SL6	• I usually try to buy products with a sustainable label.	
SL7	• Products with sustainability label are usually more sustainable than products without such a label.	
	LOCAL FOOD SUPPLY	(Żakowska-Biemans et al., 2019),(Likoudis et al., 2016), (Hempel and Hamm, 2016b)
LFS1	• I buy food products directly from the farmer.	
LFS2	• I buy locally produced food.	
LFS3	• Food products' geographical origin is a purchase criterion for me.	
LFS4	• I am willing to pay more for locally produced food.	
	TRACEABILITY	
TR1	• I am familiar with QR codes used in product traceability.	(Cavite et al., 2022)
TR2	• I have already purchased a product with a QR code for traceability.	
TR3	• I am familiar with food products package with a QR code for traceability information.	
TR4	• I regularly scan QR codes for food products traceability.	
TR5	• With food products being equal, I opt for those with QR codes for traceability.	

	ATTITUDE TOWARDS PURCHASING FROM RESPONSIBLE ENTERPRISES	
ATT_RE1	• Purchasing from a responsible enterprise is good.	(Bianchi et al., 2021)
ATT_RE2	• Purchasing from a responsible enterprise is desirable.	
ATT_RE3	• Purchasing from a responsible enterprise is nice.	
ATT_RE4	• Purchasing from a responsible enterprise is favorable.	
ATT_RE5	• Purchasing from a responsible enterprise is positive.	
	BEHAVIOURAL INTENTION TOWARDS FOOD WASTE REDUCTION	
INT1	• My purchasing choices aim at not throwing food away.	(Mondéjar-Jiménez et al., 2016),
INT2	• My consumption choices aim at not throwing food away.	(Żakowska-Biemans et al., 2019)
INT3	• I will try to modify my behaviour not to throwing food away.	
INT4	• In the near future I intend to reduce the amount of wasted food by paying more attention to my purchases.	
INT5	• In the near future I intend to reduce the amount of wasted food by paying more attention to my portions.	
	PERCEIVED BEHAVIOURAL CONTROL	
PBC1	• Finishing all food on my plate is usually easy to me.	(Lorentz- Walther et al., 2019)
PBC2	• I could always finish all food on my plate if I wanted to.	
PBC3	• Predicting the right amount of food at food choice is easy	

7.4 Results

The results of the internal and measurement models' validation are presented in this section.

7.4.1 Assessment of the measurement model

For all latent variables, the reflexive measurement method is adopted (Garson, 2016). There is reliability in the indicators; it is possible to assume that all items are expressions of the latent variables because the values of outer loadings are greater than 0.7; only the item related to the variable local food supply (LFS1), which is less than 0.7, was eliminated as it was not an expression of the variable. Indeed, for the model to be well-fitted (Garson, 2016), the values of the outer loadings must be greater than 0.7.

7.4.1.1 Construct reliability and validity

We started with the analysis of the reliability of internal consistency in order to validate the model. In particular, for the internal consistency of the model, we used Cronbach's alpha. It is good if the value is higher than or equal to 0.8.; 0.7 is acceptable, and 0.60 is for exploratory purposes (Garson, 2016). For evaluating convergent validity in a reflexive model, composite reliability (Rho_a, Rho_c) is used instead of Cronbach's alpha because it may overestimate or underestimate the reliability of the scale. Indeed, composite reliability may result in higher estimates of true reliability. The range of this value is 0 to 1, with 1 representing the estimated perfect reliability. The values of composite reliability in an appropriate model for exploratory purposes should be equivalent to or higher than 0.6, equivalent to or higher than 0.7 in an appropriate model for confirmatory purposes, and ultimately equivalent to or higher than 0.8 for a valid model for confirmatory research (Garson, 2016). However, very high composite reliability (greater than 0.90) may indicate problems of redundancy in the indicators for a given variable; thus, it is up to the researcher to assess whether the extremely high composite reliability represents this design flaw or whether the indicators are accurate but turn out to be highly correlated (Garson, 2016). Another value to consider is the Average Variance Extracted (AVE), which needs to be higher than 0.5 (Garson, 2016). In the case of the model under consideration, all these values are within limits imposed for the validity of the model (Table 20).

Table 20. Construct reliability and validity

	Cronbach's alpha	**Rho_a**	**Rho_c**	**AVE**
Attitude towards responsible enterprises	0.852	0.858	0.894	0.629
Sustainable labelling	0.867	0.882	0.897	0.554
Sustainable packaging	0.823	0.824	0.883	0.654
Behavioural Intention	0.839	0.862	0.882	0.601
Local food supply	0.730	0.774	0.844	0.645
Traceability	0.903	0.922	0.928	0.721
Perceived behavioural control	0.647	0.673	0.808	0.585

7.4.1.2 Discriminant validity

We used the Fornell-Larcker criterion to assess discriminant validity. The square root of the AVE extracted by a construct must be higher than the correlation between the construct and any other construct (Garson, 2016). The square root of the AVE appears in the diagonal cells of the Fornell-Larcker criterion, and correlations are displayed below it. Table 21 highlights that discriminant validity is well established for the model examined in that this criterion appears to be met.

Table 21. Discriminant validity – Fornell-Larcker criterion

	Attitude towards responsible enterprises	Behavioural intention	Local food supply	Perceived behavioural control	Sustainable labelling	Sustainable packaging	Traceability
Attitude towards responsible enterprises	**0.793**						
Behavioural intention	0.380	**0.775**					
Local food supply	0.266	0.092	**0.803**				
Perceived behavioural control	0.263	0.353	0.080	**0.765**			
Sustainable labelling	0.335	0.174	0.269	0.057	**0.744**		
Sustainable packaging	0.438	0.265	0.389	0.135	0.479	**0.809**	
Traceability	0.195	0.029	0.242	0.040	0.283	0.249	**0.849**

Another value is the cross-loading ratio; each indicator must have a greater correlation with the variable with which it is associated; otherwise, the model is inappropriate (Garson, 2016). In that case, the model turns out to be appropriate (Table 22).

Table 22. Discriminant validity - Cross loadings

	Attitude towards responsible enterprises	**Behavioural intention**	**Sustainable labelling**	**Local food supply**	**Perceived behavioural control**	**Sustainable packaging**	**Traceability**
ATT_RE1	**0.838**	0.286	0,252	0,270	0,204	0,323	0,236
ATT_RE2	**0.774**	0.277	0,256	0,201	0,218	0,338	0,148
ATT_RE3	**0.815**	0.312	0,264	0,205	0,206	0,399	0,118
ATT_RE4	**0.717**	0.276	0,316	0,150	0,167	0,290	0,197
ATT_RE5	**0.816**	0.349	0,251	0,222	0,241	0,372	0,094
INT1	0.323	**0.800**	0,179	0,125	0,361	0,210	0,057
INT2	0.292	**0.821**	0,116	0,053	0,420	0,206	0,030
INT3	0.240	**0.676**	0,076	0,019	0,160	0,166	-0,054
INT4	0.305	**0.790**	0,127	0,054	0,138	0,201	0,026
INT5	0.310	**0.781**	0,165	0,086	0,175	0,245	0,025
SL1	0.323	0.111	**0,702**	0,198	0,121	0,303	0,222
SL2	0.179	0.085	**0,716**	0,180	0,038	0,268	0,170
SL3	0.174	0.122	**0,710**	0,204	-0,061	0,305	0,165
SL4	0.212	0.121	**0,769**	0,119	0,030	0,364	0,191
SL5	0.194	0.106	**0,802**	0,118	0,086	0,311	0,164
SL6	0.374	0.140	**0,779**	0,343	0,058	0,487	0,305
SL7	0.227	0.201	**0,726**	0,179	0,024	0,375	0,206
LFS2	0.150	0.040	0,153	**0,701**	0,043	0,210	0,201
LFS3	0.214	0.107	0,181	**0,836**	0,125	0,299	0,213
LFS4	0.258	0.069	0,289	**0,863**	0,028	0,394	0,181
PBC1	0.175	0.327	0,009	0,109	**0,845**	0,118	-0,004
PBC2	0.179	0.199	0,025	0,048	**0,749**	0,130	0,004
PBC3	0.258	0.263	0,105	0,011	**0,694**	0,064	0,100
SP1	0.338	0.214	0,369	0,333	0,089	**0,815**	0,222
SP2	0.292	0.235	0,393	0,270	0,137	**0,831**	0,215

SP3	0.388	0.131	0,411	0,386	0,091	**0,822**	0,229
SP4	0.390	0.283	0,374	0,262	0,122	**0,766**	0,137
TR1	0.155	0.046	0,137	0,150	0,093	0,183	**0,759**
TR2	0.166	0.106	0,264	0,173	0,090	0,183	**0,863**
TR3	0.160	0.053	0,198	0,187	0,067	0,203	**0,903**
TR4	0.204	-0.009	0,243	0,206	-0,014	0,189	**0,867**
TR5	0.150	-0.043	0,323	0,277	-0,035	0,271	**0,847**

7.5 Hypothesis testing/Assessment of the internal model

Completed the bootstrapping procedure, Table 23 reports the T-statistics values to check whether the coefficients of the path of the structural model are significant. In particular, Figure 19 displays the proposed research model with the values of the path coefficients and their significance level.

Table 23. Bootstrap results for the internal model

	Independent Variable	Dependent Variable	β	STDEV	T statistics	P values	Inference
H_1	**Traceability →**	**Sustainable packaging**	0.123	0.053	2.318	0.020	**Supported**
H_2	**Sustainable labelling →**	**Sustainable packaging**	0.445	0.055	8.125	0.000	**Supported**
H_3	**Local food supply →**	**Attitude towards purchasing from responsible enterprises**	0.113	0.065	1.736	0.083	**Not Supported**
H_4	**Sustainable packaging →**	**Attitude towards purchasing from responsible enterprises**	0.394	0.060	6.587	0.000	**Supported**
H_5	**Sustainable packaging →**	**Perceived behavioural control**	0.135	0.059	2.298	0.022	**Supported**
H_6	**Attitude towards responsible enterprises →**	**Behavioural intention**	0.309	0.075	4.128	0.000	**Supported**
H_7	**Perceived behavioural control →**	**Behavioural intention**	0.272	0.085	3.178	0.001	**Supported**

The path coefficient will be relevant using a two-tailed T-test with a 5% threshold of significance if T is higher than 1.96 (Garson, 2016). It can be seen from the table that, in the model under consideration, the only link that is not statistically significant is between the local food supply variable and the attitude variable; in the internal model, every other path coefficient is statistically significant. It is possible to believe that the overall model fits the explanatory purposes well. The results of this study provide an interesting contribution to the research. For the majority of variables, the structural model has the adequate predictive ability; the impact of the model's predictor variables influences the correlation between consumers' attitudes purchasing from responsible enterprises and consumers' intention to reduce waste and engage in sustainable behaviours. The results suggest that QR codes for foodstuffs traceability have a positive impact on the proneness to look for food products with sustainable packaging; thus, hypothesis H1 is supported. In addition, a clear labelling with sustainability information influences the buying decision of food products with sustainable packaging; thus, Hypothesis H2 is supported. Nevertheless, consumers' attitude is not significantly influenced by local food supply; Hypothesis H3 appears to be unsupported; thus, it can be assumed that the proneness to look for local food products does not influence consumers' attitude towards buying from responsible companies. Further, the proneness to look for sustainable packaging variable is a good predictor of attitude towards purchasing from responsible enterprises and perceived behavioural control over having plate leftovers, which in turn positively impact consumers' intention to not waste food. Thus, hypotheses H4, H5, H6, and H7 are supported.

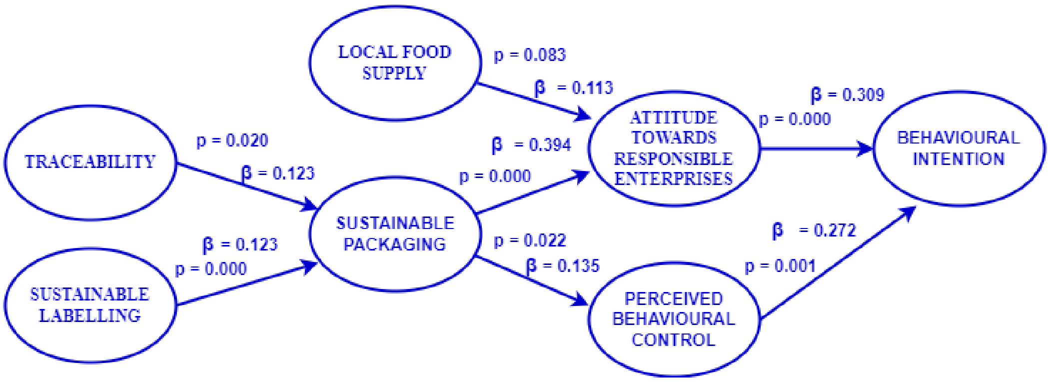


Figure 19. Research model with PLS-SEM Analysis

7.6 Discussion of the results

This research provides significant contributions to the literature on TPB in the food sector. In agreement with the results of this study are those obtained by Soorani and Ahmadvand (2019), where it was discovered that attitude significantly influences the intention to avoid wasting food. This result confirms the strongest relationships in the reference theory used. Furthermore, the strongest predictor of how much food is wasted in a household appears to be the intention to minimise food waste. Thus, through their own attitudes, consumers should be encouraged to throw away less food (Visschers et al., 2016). The analysis conducted by De Canio and Martinelli (2021) shows that attitudes towards organic food are positively affected by having recyclable packaging. In line with that, this study shows that that the proneness to buy food products with sustainable packaging positively influences attitudes towards purchasing from responsible enterprises. As a result, sustainable packaging can represent an added value for conscious consumers, who reward companies that adopt responsible practices. This has implications for companies that aim to focus on the pursuit of increasingly environmentally friendly packaging, considering the important challenge we all face to reduce the waste impact on the environment, among the goals of the 2030 Agenda. According to the results presented in the analysis by Aitken et al. (2020), labelling was discovered to be positively correlated with attitude, and enhancing labelling systems to integrate more practical and useful information, such as the health, environmental, and societal benefits of foodstuffs, would increase perceived behavioural control and strengthen purchase intentions for organic foods; more product knowledge would increase perceived behavioural control while also having a favourable impact on attitude towards purchasing foodstuffs. Thus, providing useful information will likely lead to increased rates for food products and, as such, should be a key element in management strategy. In this study, on the other hand, it is shown that food products with labelling reporting all the information about product sustainability clearly and understandably positively influence the proneness to buy food products with sustainable packaging, indirectly impacting consumer attitudes towards purchasing from responsible enterprises. Companies, therefore, are responsible for providing clear and accurate labelling so that consumers can read all the information they deem necessary on food packages and can thus help reduce food waste. According to previous studies (e.g. Hempel and Hamm, 2016), the SFSC focuses on the development of the territory, decreasing the implications of the aesthetic food standards and helping to reduce the amount of food wasted. In contrast, the findings of this study demonstrate that the purchase of local food supply does not positively influence consumers' attitudes towards purchasing from responsible enterprises. Policymakers should take action to initiate awareness campaigns to mitigate the effects of the unesthetic foodstuffs, emphasising the benefits that come out of buying short chain food products on environmental, economic, and social sustainability. Furthermore, the findings of this research show that food products' traceability information has a positive impact on consumers' decisions to buy foods packaged sustainably, which is in line with Cavite et al. (2022), showing that consumers' intention to buy organic food with traceability information is favourably influenced by its product traceability's awareness. People use product tracking to gather information and analyse it systematically, leading to an increase in their likelihood's purchase intention. Additionally, product traceability data gives consumers characteristics that boost their confidence in food safety, which is advantageous to them (Cavite et al., 2022).

7.7 Conclusions, implications, and future research directions

The theoretical and practical contributions of this research, as well as the limitations and avenues for further investigation are following below. Businesses and policymakers can employ the results of this study in designing strategies to reduce households' food waste. Indeed, this research plans to contribute to understanding the factors influencing consumers' food choices and their impact on consumers' intention to mitigate waste. The proneness of purchasing food products with sustainable packaging significantly influences consumers' attitudes towards purchasing from responsible enterprises as well as perceived behavioural control over having plate leftovers, which in turn significantly influence consumers' intention to reduce such waste. The use of sustainable packaging, thus biodegradable, recyclable, and reusable, reduces the environmental impact that results from its production and disposal; on the other hand, according to this research results, it could be a useful tool for raising consumer awareness towards food waste generation. Sustainable labelling and QR codes used for food traceability are information that positively influence consumers to purchase food products with sustainable packaging; therefore, companies should aim to improve these aspects, thereby contributing "through" consumers to reducing households' food waste. Consumers' pro-environmental behaviour and the purchase of food products with sustainable packaging may be enforced by policymakers and those who oversee packaging laws. Therefore, by highlighting the significance of foodstuffs' traceability, policymakers and authorities could conduct campaigns to promote the welfare and health of individuals. Food producers should improve their products' traceability and the benefits that come with it. Companies can increase their market share by offering goods that consumers are more willing to purchase. Sustainable labelling significantly influences consumers' purchasing behaviours. As a result, to draw consumers and give them a premium feel, marketers should strategically design the information provided on the sustainable label. For instance, the clear mention of CO_2 emissions reduction on product labels and packaging may draw customers' attention and encourage them to purchase a particular item. These results are significant for both researchers and practitioners, and they are particularly pertinent in light of SDG 12.3. The results of this analysis imply that consumers have been increasingly understanding the importance of reducing food waste and are inclined to purchase sustainable food products; food companies need to invest by aiming to downsize their production systems by increasingly applying technologies and practices of sustainability and CE.

Although this survey has some limitations, these could serve as an entry point for new research directions. First, more interviews could be conducted to increase the sample size. Further, although the data of the variables are considered valid and reliable, it is possible that some consumers who took part in the survey provided socially desirable responses, although to remedy this problem, the survey's anonymity was guaranteed to the participants. In addition, it should be noted that the data were gathered for this survey at a specific time and related to Italian consumers; therefore, they take a snapshot of the situation at a specific time instant and are limited to a specific geographic area.

Future research could expand the analysis by surveying consumers coming from different countries. Conducting a multi-group analysis, which allows for analysing whether established data groups have significant differences in their estimates of the PLS model parameters, is another recommendation for future research developments.

8. General conclusions

This Ph.D. thesis aimed to investigate how agribusinesses can redesign their supply chains to meet the newly emerging needs of sustainability and CE and foster green innovation. The investigation results not only promote environmental sustainability but can also contribute to the long-term success of agri-food companies in the context of a growing global focus on environmental and social responsibility.

The systematic and bibliometric analysis of the literature allowed us to uncover the research field's structure, thoroughly examine the literature in relation to each cluster identified and suggest promising directions for further qualitative and quantitative studies. Notably, adopting two independent methods (i.e. descriptive cluster algorithm in Chapter 3 and co-citation analysis of cited references in Chapter 4) to highlight the primary research clusters of the field of inquiry led to similar conclusions, thus confirming the robustness of the literature review results. Subsequently, in Chapter 5, based on the research gaps previously identified, the empirical analysis allowed us to explore how agri-food companies can be promoters of a sustainable and digital transition, reducing the amount of FLW and the overall environmental impact both upstream and downstream of the supply chain. To achieve this objective, agri-food industry leaders must fundamentally re-evaluate their business practices, develop and implement new digital technologies and circular practices, and choose a long-term shared value creation mindset over short-term efficiency and profit, thus promoting more efficient and sustainable production and consumption systems. The choice of multiple case study approach allowed us to analyse the phenomenon in-depth, going far beyond what happens in the individual company, but trying to understand what happens throughout the agri-food supply chain. Indeed, through the semi-structured interviews, it was possible to identify the main causes of FLW across the value chain and highlight the most effective and most used practices and technologies adopted by Italian food and agri-food companies to avoid such wastes, as well as the main barriers related to their implementation. In addition, we uncovered the main drivers that pushed companies towards the sustainable and digital transition, which arise from coercive pressures from all stakeholders, external, internal, primary, and secondary, which through supplier selection criteria and laws push companies to implement their strategies to align them with the 2030 Agenda SDGs. This highlights how different institutions, suppliers, customers, and all stakeholders play a key role in the implementation of certain practices and how each of these, in different ways, impacts the level of adoption. Larger companies may thus motivate other firms, even in different geographical locations, to implement sustainable practices through precise selection criteria and guidelines. The impact of such pressure is certainly the strongest. However, it differs according to the characteristics of the companies, which proactively adopt such practices in some contexts, while in others, they need help to implement the strategies. In addition, the results show an increasing awareness among companies regarding CE and digitalisation paradigms. However, from the analysis, many companies still need to implement these models effectively. Most of the surveyed companies believe that implementing CE practices positively impacts brand reputation while also increasing competitiveness. At the same time, companies often find it difficult to manage product diversity and reverse logistics, highlighting the need for more effective and easy-to-implement strategies and solutions. Overall, the analysis revealed that CE strategies are more widespread and implemented than I4.0 technologies across the supply chain, and that both are used more upstream of the food chain to valorise waste rather than to prevent its generation. As a result, the agri-food industry needs to apply further practices and tools in their production and distribution processes to have a greener and lower environmental impact. Downstream the results of the multiple case study analysis, in order to quantitively demonstrate the environmental advantages of employing circular strategies in the agri-food sector, the LCA approach was implemented (Chapter 6). The egg industry was chosen as a case study because its complex network of activities reflects the general dynamics of the agri-food industry in terms of production, transportation, and marketing, requiring great attention to product quality, food safety and security, sustainability, and responsiveness to market needs. As a result, this choice allowed us to generalise the results beyond this specific industry to the broader agri-food domain. Notably, the LCA analysis highlighted how supplier selection and the product's packaging are fundamental drivers of the environmental effects in fresh food distribution. As a result, a low environmental impact can be achieved by changing the food production and distribution systems entirely, with a focus on local production, and using natural and biodegradability resources coming from agricultural waste, such as PLA, which can be a great way to adopt an eco-friendly approach to packaging for the agri-food industry context. In addition, these findings suggest that companies' managers should use the environmental product declaration (EPD) to spread information about the environmental impact of their products and services and consequently increase sales. Indeed, exploiting the findings of the LCA analysis, the environmental effects connected to the product's life cycle, such as a reduction in CO_2 emissions, might be made explicit on product labels and packaging, attracting customers' attention and encouraging them to purchase products with a sustainable label. The EPD offers verified information on how well products and services perform regarding the environment. It is a vital component for businesses looking to stand out from the competition by providing extensive information on the environmental impact of their products so that consumers can make better-informed decisions. Indeed, particular attention must be paid to the consumer, as he or she is often the main cause of food waste, directly, as he or she wastes everything close to the expiry date or everything that spoils due to improper storage but also indirectly, through high aesthetic standards, inducing farms, producers, and sellers not to put on the market everything that appears non-compliant and unsuitable, even though edible. With increasing environmental challenges, the general attention of the global community is largely being shifted towards promoting sustainable production and consumption practices. Private consumption contributes significantly to increasing carbon emissions, leading to environmental degradation and increasing risks to social sustainability. In order to achieve the SDGs, there is a high need to improve consumer purchasing choices by taking into account the positive effects of sustainable consumption on environmental sustainability. Through the multiple case study analysis conducted in Chapter 5, we revealed that the SFSC, blockchain technology for traceability of foodstuffs, and sustainable food labelling and packaging are key strategies and tools that could help not only to reduce the environmental implications of the upstream stages of the value chain but could also help consumers make more sustainable purchases and raise their awareness towards food waste reduction. However, the qualitative nature of the case study did not allow us to establish causality. As a result, we finally carried out a quantitative survey to contribute to understanding the factors that influence consumers' food choices and their impact on consumers' intention to reduce food waste (Chapter 7). According to the PLS-SEM results, sustainable labelling and blockchain-based QR codes used for food traceability are information that positively influences consumers to buy sustainably packaged foodstuffs. In addition, the proneness to buy food products with sustainable packaging significantly influences consumer attitudes towards purchasing from responsible enterprises and perceived behavioural control over having plate leftovers, which in turn significantly influence consumer’s intention to reduce waste. Businesses and policymakers can consider these results in defining strategies to mitigate households' food waste. On the other hand, using blockchain technology to track and trace foodstuffs and using sustainable, recyclable, and reusable packaging with a sustainable label can reduce the environmental impact of the production, distribution, and disposal phases. Therefore, companies should aim to implement these factors, thus contributing to developing more sustainable production and consumption of food systems upstream and downstream of the agri-food supply chain. It is worth noting that companies that want to embrace the sustainable and digital transition need to redesign plants, products, and the entire supply chain. Therefore, they also need to build an effective system of skills and knowledge within the company, as well as an external system of synergies and coordination to spread the culture of sustainability not only to all levels of the company but to the entire FSC. A crucial aspect is communication between the different stages of the production chain. The comprehensive analysis revealed the urgency of creating and implementing digital platforms to improve coordination between the FSC actors to receive and analyse sales data in real-time and optimally align production and consumption; this could be achieved through I4.0 technologies (e.g. blockchain). It is important to emphasise, however, that the implementation of such practices is not only a cost but a long-term investment leading to environmental benefits and the achievement of economic goals; this is of paramount importance, especially for companies with a smaller turnover, which are confronted with high investments due to a low degree of technological implementation and CE. These barriers must be kept in check, as they are the cause that prevents the CE and sustainability from becoming part of our daily lives.

As a result, this research contributes both to the theory and practice in the field. From the theoretical perspective, this research extends the Institutional theory and Resource-based view theory by shedding light on the primary external and internal driving forces leading agribusinesses to embrace the digital and sustainable transition. In addition, our investigation contributes to the Theory of Planned Behaviour by highlighting the key technologies and practices influencing consumers' attitudes and intentions towards food waste mitigation. Regarding its contributions to the industry, this wide investigation identifies the main factors leading to FLW across the value chain. In addition, it offers suggestions on how agribusinesses can incorporate I4.0 technologies and CE procedures to manage and reduce FLW effectively. Additionally, this study quantifies the effects of significant digital innovations and CE practices on environmentally friendly consumer behaviour, showing how these tools can not only reduce the environmental implications upstream of the agri-food supply chain but also downstream at the households' level. Additionally, this study quantitatively evaluates and compares the environmental impacts of various CE initiatives that agribusinesses can employ, offering the most beneficial environmental solution compatible with companies' economic and financial constraints. As a result, this broad investigation is intended as an awareness-raising and guidance tool for agribusinesses, stakeholders, and policymakers, highlighting the challenges, opportunities, and virtuous practices within CE and digitalisation, trying to help move businesses and society towards a more sustainable and resilient future.

This study focuses on Italian agribusinesses and consumers but can be extended to other geographical settings to observe similarities and differences. Notably, future research may use a longitudinal approach to assess the effectiveness of CE practices and digital technologies over time. In addition, future studies could use the Interpretive Structural Modelling (ISM) approach to define the links between technologies, practices, and corporate performance (i.e. economic, environmental, and social performance), classifying them according to their driving and dependency powers. Notably, this approach could identify which practices lead to other practices to improve performance and by which precise technologies they are driven. Furthermore, as explained in the previous Chapters, an important issue concerns the expiry date. Future research could go in this direction and analyse the consumer's perception of the 'best before' and 'use by' labels, offering suggestions and insights on improving the labelling systems. Notably, future studies should focus on consumers' perception of intelligent food packaging, i.e. packaging that can reveal the condition of the food through appropriate sensors, certifying and keeping track, via blockchain technology, of the different stages the food product has undergone. This kind of packaging could significantly decrease the amount of food wasted in households. Therefore, it is necessary to investigate this topic further, as misunderstanding the expiry date is one of the main food waste factors identified. Finally, future research should focus on developing an evaluation system for food waste valorisation technologies. Indeed, as highlighted in this study, agri-food waste can be valorised using different facilities (e.g. biogas and composting plants) depending on the nature of the waste and the value chain under investigation, and the uncertainty of the decision-making process makes it difficult to make the right technological decision. As a result, it will be possible to adopt a multi-criteria decision-making approach, such as combining the analytical hierarchy process (AHP) and the fuzzy set theory, to assign a weight to each considered parameter (e.g. economic, environmental, and social factors), rank the various food valorisation technologies according to the evaluation criteria, and determine the most suitable solution.

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