UNIVERSITÀ DEGLI STUDI DI PADOVA
DIPARTIMENTO DI INGEGNERIA CIVILE, EDILE E AMBIENTALE
Department Of Civil, Environmental and Architectural Engineering

Corso di Laurea Magistrale in Environmental Engineering

TESI DI LAUREA

Utilization and Impact of Internet of Things (IoT) in Food Supply Chains from the Context of Food Loss/Waste Reduction, Shelf-Life Extension and Environmental Impact

Relatore:
Chiar.mo PROF. Alessandro Manzardo

Laureando: Işıl Doğan
2050928

ANNO ACCADEMICO 2022-2023

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Abstract

Background: The Internet of Things (IoT) sensor-based technologies are transforming the realm of food production and consumption by offering the potential to enable real-time tracking and data sharing, thus improving communication in the food supply chain. Specifically, real-time information on the location and state of food products as they travel from farms to processing plants, distribution hubs, and eventually consumers can be provided via IoT-enabled sensors and devices. This enables prompt reaction to deviations from ideal circumstances, delaying spoiling and minimizing food loss and waste (FLW). This approach also allows for dynamic inventory management, mitigating issues of overstocking and understocking often linked to food loss.

Research gaps: However, the current literature rarely discusses the extent to which the implementation of such technologies can contribute to the mitigation of FLW remains uncertain.

Objectives: The objective of this study is to conduct an extensive and systematic literature review to analyze the use and effects of IoT in food supply chains, with an emphasis on its potential to extend the shelf life of food products and decrease FLW across the entire value-added chain. Meanwhile, our study aims to examine the impact of IoT technology integration on environmental, economic, and social aspects from an Life cycle assessment (LCA) perspective. First, the study conducts a systematic literature review to spotlight crucial potentials, identify gaps between previous studies, and delineate future trends by using IoT-enabled technologies in the food supply chain. Second, this study aims to analyze the key characteristics of food sectors spanning from "farm-to-fork" within the IoT domain and instigate how IoT-based technology solutions influence the evolution of shelf lives and food losses across various food products as they progress through the value-added chain. Third, this study is to examine the potential of an effective IoT-based monitoring system in food systems from the life cycle environmental, economic, and social aspects. Particularly, it seeks to assess whether the potential adverse effects stemming from technological production and waste outweigh the environmental advantages associated with avoided FLW, as well as the extension of shelf life.

Literature results analysis (preliminary): This review analyzed 77 research papers on IoT technologies for mitigating FLW across the value-added chain. This study then categorized these papers by publication year, type, food category, and supply chain stage. The findings reveal a rising trend in publications from 2008 to 2022, with an initial lack of interest in the early years. "Sensors" and "Food Control" were prominent journals in publishing related articles, while various other journals also contributed. Notably, research encompassed multiple food groups, with a focus on fruits, meat, and fish, highlighting IoT's potential in managing perishable goods. Storage, transportation, distribution, retail, and manufacturing stages received research attention. China led in the number of articles, reflecting global interest, and international collaborations were evident, showcasing IoT's applicability to FLW worldwide.

Discussion and limitation: Even though varied goals and localized emphasis of studies provide insightful information; standardization and a more thorough approach are required for further study. Simplifying the use of technology throughout the food supply chain can have a major positive impact on the environment and the economy worldwide.

Conclusion and future outlook: The studies demonstrate how technology is revolutionizing the food supply chain by minimizing food loss and waste via environmental control, real-time monitoring, and early spoilage detection. While highlighting the advantages for the economy and the environment, they also stress the significance of customized approaches for various food categories. Notwithstanding these drawbacks, the outlook for the future points to a sustainable, data-driven, networked supply chain that puts customer satisfaction first and waste reduction first.

Keywords: FLW, Shelf life, Environmental impacts, IoT, Real-time, Sensor, LCA

1. Introduction

1.1. Background and purpose

The need for a swift transition to an environmentally sustainable food system is pressing (Clark et al., 2022; Crippa et al., 2021). If technology and behaviors in the food system persist along recent trajectories, international climate and biodiversity targets would then elude us in the coming decades. While the socio-economic consequences, such as increased public costs, labor demand, and food prices, are easily observable in everyday life, the environmental impacts associated with food loss and waste (FLW) pose a challenge as they remain hidden and are not immediately recognizable by companies, consumers, and governments (Amicarelli and Bux, 2021; FAO, 2013). A crucial stride toward achieving international and regional targets for reducing FLW is to evaluate and then forecast the potential of sensor-based solutions leveraging digital technologies, facilitating the transition toward an environmentally sustainable food system.

Industry 4.0 comprises a wide range of cutting-edge digital technologies and solutions, including robots, the Internet of Things (IoT), artificial intelligence (AI), and smart sensors. These developments have the potential to hasten automation and the uptake of digital practices across a range of industrial sectors, including the food sector (Hassoun et al., 2023). The integration of the IoT into food sectors offers several advantages, including better refrigeration, real-time quality monitoring, optimized delivery routes, and improved distribution methods. Recent advancements in food supply chain optimization primarily revolve around extending the shelf life of perishable items and reducing FLW during the storage or distribution process. Practical examples have been successfully applied to various perishable foods, enabling real-time management and predictive capabilities for extending shelf life and decreasing FLW (Zhu et al., 2022).

The introduction of IoT has brought about significant transformations and complexities within the food supply chain, impacting both the supply chain itself and environment impacts. It is estimated that applying IoT and sensor technologies in 50–75% of supply chains in developed nations by 2030 could lead to a reduction of food loss by 10–50 million tons during distribution, highlighting environmental benefits caused associated with FLW prevention and mitigation. However, only a limited number of individuals express concern regarding the environmental sustainability implications of the widespread adoption of IoT. It is crucial to account for the environmental challenges associated with sensor manufacturing, operation, and electronic waste disposal that arise with the widespread adoption of IoT since this is conducive to directing the development of design and leveraging enabling technologies in an environmentally beneficial way, particularly in the context of food-specific sensor modules. Therefore, considering potential life cycle trade-offs in relation to the integration of IoT into the food supply chain is necessary (Zhu et al., 2022; Luo et al., 2022).

The main purpose of the research is to perform a comprehensive and systematic review of the literature, focusing on the utilization and outcomes of IoT technology within food supply chains. Our emphasis is on its capacity to prolong the shelf life of food products and reduce FLW across the entire value-added chain. Additionally, our study aims to evaluate the ramifications of incorporating IoT technology on environmental, economic, and societal dimensions, adopting a Life Cycle Assessment (LCA) perspective. We seek to ascertain whether the potential negative consequences arising from technological production and waste outweigh the environmental benefits associated with FLW reduction and shelf-life extension. The findings provide comprehensive insights for guiding the implementation of data-driven IoT-enabled technologies in the food supply chain. Particularly, this review can assist in informing and shaping effective food waste policies and strategies through the utilization of such advanced technologies.

1.2. Gaps and challenges

The application of food sensing technologies, rooted on the IoT, holds significant promise for revolutionizing food supply chains (Holden et al., 2018). This emerging field offers opportunities for precision, traceability, visibility, and controllability. The exponential growth of sensor-based solutions in reducing FLW also presents a vast potential for generating valuable data in this context. Despite the increasing interest in food sensing technologies within the IoT application domain, their potential to effectively and sustainably reduce FLW remains questionable.

Firstly, while the IoT-based technologies theoretically enable real-time tracking and data sharing, improving communication in the food supply chain, the main characteristics of food sectors from “farm-to-fork” in the context of the IoT domain still require empirical validation. Variations in food types, technology usage, geographical locations, research methodologies, and other factors across studies introduce challenges in comprehending the actual impact of these technologies. This underscores the need for a comprehensive review of all pertinent studies to identify disparities and commonalities, thereby providing guidance for future research studies.

Secondly, the scarcity of knowledge regarding the utilization of IoT-based real-time monitoring technologies within the food industry, along with the associated practices (Costa et al., 2023), underscores the necessity for a meticulous and systematic exploration of the potential applications of intelligent monitoring technologies to tackle issues within the food supply chain (Costa et al., 2023). A commonly accepted approach to address this need is the evaluation of the impact of these technologies on extending shelf life and reducing FLW across the value-added chain.

Thirdly, in addition to understanding penetration of sensor technologies into the food supply chain and its uses to solve possible problems, the integration of these technologies necessitates an exploration of potential life cycle trade-offs, with a particular focus on environmental impacts like carbon mitigation (Lou et al., 2022). However, studies employing Life Cycle Assessment (LCA) to assess these trade-offs are exceedingly limited. Consequently, there is an imperative to scrutinize existing research and highlight the demand for additional investigations in this area.

1.3. Objectives of the study

The objective of this study is to conduct an extensive and systematic literature review to analyze the use and effects of IoT in food supply chains, with an emphasis on its potential to extend the shelf life of food products and decrease FLW across the entire value-added chain. Meanwhile, our study aims to examine the impact of IoT technology integration on environmental, economic, and social aspects from an LCA perspective. It seeks to assess whether the potential adverse effects stemming from technological production and waste outweigh the environmental advantages associated with avoided FLW, as well as the extension of shelf life. Therefore, the objective of this study can be summarized as follows:

- I. Conduct a systematic literature review to spotlight crucial potentials, identify gaps between previous studies, and delineate future trends by using IoT-enabled technologies in the food supply chain.
- II. Analyze the key characteristics of food sectors spanning from “farm-to-fork” within the IoT domain and instigate how IoT-based technology solutions influence the evolution of shelf lives and food losses across various food products as they progress through the value-added chain.
- III. Examine the potential of an effective IoT-based monitoring system in food systems from the life cycle environmental, economic, and social aspects.

1.4. Research framework

A key step toward achieving international and regional targets for reducing FLW is to evaluate and then forecast the potential of IoT-based solutions leveraging digital technologies, facilitating the transition toward an environmentally sustainable food system. To provide a comprehensive depiction of the potential of these technologies within the food system, the framework of this study is shown in Figure 1.

Section 1 outlines the study's context and purpose. It identifies gaps and challenges from prior research and outlines the three primary objectives of examining the potential of IoT-enabled technologies in the food supply chain.

In section 2, key terms and concepts related to IoT technology and food systems are defined. This section underscores the theoretical underpinnings that elucidate the role of IoT-based technologies in extending shelf life and curbing FLW throughout the value-added chain.

Section 3 describes the scope and main methodologies used in conducting the literature review. Within this section, articles spanning a 20-year timeframe are identified and retrieved via the WoS database. These articles are subsequently subjected to screening and analysis using tools such as Google Sheets, Visio, Originlab, and VOSviewer. This comprehensive approach aims to visually depict research trends, pinpoint hot topics, and map diverse bibliometric networks throughout the food supply chain (excluding consumption stages).

Furthermore, all available data will be elucidated through selected methodologies to highlight differences and similarities in evaluations (section 4), aiming to determine if there is a need for a more systematic research method to comprehend the net impact of IoT technologies on food supply chains.

Additionally, the review will discuss the main gaps in the literature and the necessary improvements required to obtain clear and comparable data in future research studies (section 5).

Lastly, section 6 provides a summary of the key findings derived from the analysis of the literature review.

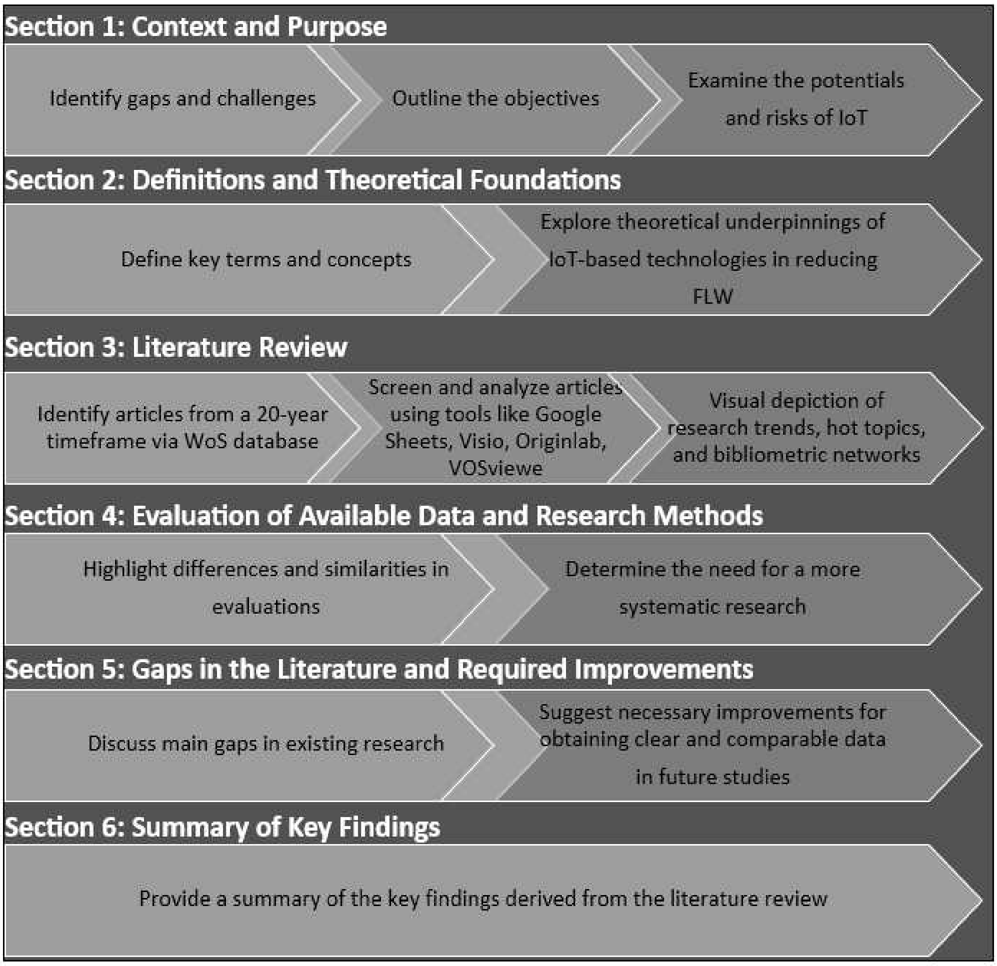

Figure 1: Overview of the framework for conducting the thesis

2. Theoretical foundations

With the growing global awareness of sustainability and environmental responsibility, efforts to reduce food waste generation, energy consumption, and water usage within the food supply chain (FSC) are becoming more and more important. The Internet of Things (IoT) has become a transformative force in this context, allowing FSC actors to tackle these challenges holistically. The idea behind the Internet of Things (IoT) began in the Auto-ID labs in 1999. Kevin Ashton invented RFID technology, which was used to connect objects in this system. But the Internet of Things (IoT) has expanded to include low-power processors connected to the internet, which allow physical objects to be sensed and controlled. It is categorized as a cyber-physical system and finds use in grids, intelligent transportation systems, smart cities, and smart homes. Several enabling technologies, such as RFID, wireless sensor networks, data analytics, cloud computing, and internet protocols, are combined to form an Internet of Things system. The Internet of Things was founded on RFID technology, which is still developing. It functions by transmitting stored data about objects or people via radio waves. Wireless Sensor Networks (WSN) can keep an eye on product conditions. They are made up of dispersed sensor networks that can self-network, use less power, and require less human interaction. WSNs use different wireless standards, such as Wi-Fi, Bluetooth (Smart), ZigBee, and Near Field Communication (NFC), to facilitate data transmission. Another essential element of IoT is cloud computing, which serves as a platform for storing sensory data. It also permits analytical and computational operations on the gathered data and offers centralized access to the services that are produced. A key component of deriving meaningful insights from large datasets is data analytics. It entails applying machine learning algorithms to build predictive models that improve the ability to make decisions. In order to guarantee food safety and quality throughout the entire food supply chain, these technologies are being adopted by the industry. Notably, tracking, tracing, and monitoring have been the main areas of IoT solution focus. The fundamental power of IoT is found in data-driven models that provide useful business benefits. The copious amounts of data produced by sensors can be utilized to create an information network that facilitates efficient decision-making and product management along the entire supply chain. However, integrating cloud computing tools with IoT devices is necessary to make this network feasible (Nukala et al., 2016; Jagtap et al., 2021).

This technology is structured around a four-layered architecture: the Sensing Layer, the Network Layer, the Service Layer, and the Application Layer. Each layer plays a distinct role in gathering data, processing it, and delivering meaningful insights to users, with the ultimate aim of minimizing energy and water consumption and reducing food waste within FSCs.

1. Sensing Layer: At the foundation of the IoT architecture is the Sensing Layer. This is where data related to energy, water, and food waste is collected. A diverse range of sensing technologies is employed, including load cells, smart meters, sensors, cameras, and RFID tags. Smart meters, specialized for measuring energy

and water consumption, are vital components of this layer. To track food waste, load cells and image processing technology are employed for solid food waste, while liquid food waste is monitored using dedicated smart meters. The Sensing Layer is the frontline in data acquisition, ensuring that all critical information is captured accurately.

2. Network Layer: The Network Layer serves as the bridge between the Sensing Layer and the subsequent processing stages. It is responsible for transmitting the data collected in the Sensing Layer to the Service Layer. Modern communication technologies such as Wi-Fi, Bluetooth, and various electronic devices and hardware like Arduino and Raspberry Pi are deployed to facilitate this transfer. This layer ensures that data flows seamlessly from the point of collection to the analysis and storage stages.

3. Service Layer: Within the Service Layer, the data collected from the Sensing Layer is stored, either in the cloud or on a local server. It serves as the repository for the massive amounts of data generated within FSCs. The data is then subjected to analysis using advanced data analytics platforms. This analysis is instrumental in extracting meaningful insights and patterns, transforming raw data into actionable information.

4. Application Layer: The topmost layer of the IoT architecture, the Application Layer, delivers the value of the entire system to stakeholders and users. It offers user-friendly applications and services designed to empower decision-makers within FSCs. These applications provide accurate and real-time data, enabling stakeholders to manage projects focused on resource consumption reduction and waste minimization. They act as the interface through which users interact with the insights and recommendations generated by the IoT system, making informed decisions, and taking actions to enhance resource efficiency.

This four-layered IoT architecture is tailored to the specific requirements of FSCs, providing a robust framework for addressing the challenges of energy and water consumption, as well as food waste reduction. By seamlessly integrating data collection, transmission, analysis, and application, IoT technology is instrumental in driving sustainable practices and resource optimization within the food supply chain (Jagtap & Rahimifard, 2019).

An atmosphere that is conducive to revolutionary changes is created by the gathering of trustworthy, real-time data. Equipped with these insights, FSCs can encourage staff members to adopt new behaviors and carry out operational enhancements. Food waste can be significantly decreased by investing in more effective equipment and procedures, which can be informed by the data collected. Moreover, a comprehensive picture of the supply chain's performance is provided by the integration of these IoT devices with Enterprise Resource Planning (ERP) systems, empowering supply chain participants to anticipate and respond to last-minute order changes by knowing how they will affect waste generation, which it contributes to FWL. When it comes to energy efficiency, IoT technologies offer innovative solutions. Real-time monitoring of energy consumption is conducted by smart energy meters and sensors that are integrated into IoT systems. Supply chain participants can gain a detailed understanding of energy usage patterns with the help of this data. Energy consumption inefficiencies can be found and reduced with careful analysis. IoT technologies help lower energy costs and lessen the carbon footprint of FSCs by, for example, identifying machinery that consumes excessive amounts of energy or optimizing production schedules to minimize energy usage. Better energy efficiency comes with cost savings and environmental advantages, which is why FSCs find IoT applications appealing. A vital component of sustainability in the FSC is water management, in addition to energy and food waste. Water is a valuable resource that is utilized in many phases of cleaning, food production, and other operations. Water waste and overconsumption have serious negative effects on the environment and economy. Smart water systems built on the Internet of Things are prepared to take on these difficulties. Through the process of tracking water usage at various points in the supply chain, these systems are able to quickly identify any non-standard consumption patterns. IoT-driven alerts cause prompt responses to issues like leaks and excessive use of water resources. Due to the proactive handling of water-related issues made possible by this real-time capability, overall water consumption is significantly reduced. As a whole, IoT technologies have brought about a revolution in the management of waste, energy, and water resources in food supply chains (FSCs). These technologies offer real-time visibility, data-driven insights, and automation capabilities. In addition to promoting cost savings and operational excellence, this digital transformation also brings FSCs into line with the expanding international commitment to environmental responsibility and sustainability. With the world's environmental problems getting worse, IoT is going to be essential to building more sustainable and effective food supply chains (Nukala et al., 2016; Jagtap et al., 2021).

The use of IoT technologies at some stages of the food supply chain (FSC) is explained in detail as follows. The production phase within the realm of the Internet of Things (IoT) plays a pivotal role in elevating agricultural practices and optimizing livestock management. This phase is marked by a surge in precision agriculture, harnessing the capabilities of IoT devices, wireless sensors, and mobile technology. These technological assets are proving to be indispensable to modern-day farmers. In the context of precision agriculture, IoT devices give farmers accurate and up-to-date information about a variety of parameters that are essential for improving farming practices and growing fresh produce. A few examples of these parameters are water irrigation, pest and fertilizer management, farming equipment, soil quality, and greenhouse production environments. At the forefront of this technological revolution are Wireless Sensor Networks (WSNs), which allow for the real-time monitoring and control of these crucial variables. There are some studies concentrated on the use of WSN-integrated precision agriculture systems, including closely monitoring crop health and environmental conditions, automating irrigation systems, and optimizing crop cultivation. Interestingly, WSNs and GPS systems have been successfully integrated, enabling the collection of exact location data in the areas that are being observed. Moreover, current research efforts have focused on integrating cloud computing with Internet of Things devices. The development of services, data visualization, centralized data access, safe information storage, and efficient product distribution are just a few of the many uses for this integration. The benefits of cloud computing can be extended to planting management, farm management, and the tracking and control of agricultural products. This connected, networked farming approach has the potential to simplify farming practices, which will ultimately result in increased productivity. The introduction of IoT technologies has also resulted in a significant transformation in livestock management. In this field, the use of sensing technologies has been expanding quickly. Radio Frequency Identification (RFID) technology is particularly notable because it has strong applications for traceability during the production process. For example, RFID systems have been suggested for managing and tracking different kinds of livestock and live fish. WSN deployment has also shown promise in tracking cattle grazing and other aspects of livestock management, as well as in monitoring animal behavior. Nevertheless, the application of animal-based sensors and technology in livestock management has brought about its own set of challenges. These include concerns about device safety, the cost of installation, data retrieval, and data management (Nukala et al., 2016).

Transportation and distribution play a critical role in the safe handling of perishable foods, which are highly sensitive to temperature fluctuations and improper management. The burgeoning consumer consciousness surrounding food safety, freshness, and traceability has facilitated the creation of intelligent systems through the Internet of Things (IoT). At first, RFID systems were mainly used for product tracking; however, they were devoid of sensing capabilities, which are essential for determining how fresh a product is. IoT systems began fusing RFID with sensor technology to get around this restriction, which opened up a plethora of new applications. The two main focuses of these applications are "business" and "supply." In order to improve the efficiency and integrity of the product, the business aspect includes environmental monitoring and product traceability. RFID and temperature sensor integration has shown to be essential in cold chain applications, vineyards, fish supply chains, and perishable product monitoring (e.g., meat, fruit, and juice). Monitoring systems have been greatly enhanced by the combination of RFID technology and Wireless Sensor Networks (WSNs). WSNs are now used in cold chains to give perishable product temperature data in real time. Numerous investigations have examined the developments in monitoring systems, demonstrating their capacity to completely transform the sector. The actual worth of the produced data is found in helping different stakeholders work together by managing information well. It has been suggested to monitor and ensure the quality of perishable goods using a context-aware WSN-based system. Estimating a product's shelf life is also necessary to ensure food quality. There are now decision support systems that use algorithm-based models and time-temperature indicators to predict shelf life. These systems offer significant value in addition to being economical and efficient. Other factors to take into account, besides estimating shelf life, are stock rotation and prompt product recall in the event of a food safety incident. Internet of Things (IoT) applications have made great progress in warehouse and shipping container management with respect to the supply side of the Food Supply Chain (FSC). Capacity sensing, planning, reporting, route optimization, energy management, and fault detection are some of these applications. Mobile-based tools for fleet management, pricing frameworks, and inventory management have all been shown in other studies. Additionally, intelligent containers that preserve perishables' quality have been developed technologies have progressed in recent years to create intelligent cloud-based information sharing systems. Using sensor and cloud technologies, some researchers have developed architectures that enable real-time data processing and monitoring. With an emphasis on food safety, these architectures have also prioritized information identification, sharing, tracking, and tracing. IoT applications in distribution and transportation are expanding, and research suggests that there is still more to learn about areas like cost-effectiveness, security, and efficient teamwork. Predictive models are increasingly being created using machine learning algorithms, and the creation of entire IoT systems requires the fusion of knowledge from many domains (Nukala et al., 2016).

A paradigm shift has occurred in the retail industry as a result of the integration of Internet of Things (IoT) technologies, completely changing how businesses run, handle their supply chains, and interact with consumers. The use of loyalty card systems has been one of the most early and significant innovations in this field. Originally intended as consumer-attracting marketing tactics, these systems have developed into effective instruments for comprehending consumer behavior and preferences. Retailers can obtain invaluable insights by applying data mining techniques to transaction data related to loyalty cards. One well-known example is a U.S. supermarket that increased sales of beer significantly among fathers who also purchased diapers by placing beer displays next to the diaper section. On-shelf availability (OSA) is also a crucial component in providing customers with fresh produce. Out-of-stock merchandise can make for a bad shopping experience. Retailers can anticipate and avoid these kinds of scenarios with the aid of IoT-enabled OSA systems, which lowers the out-of-stock rate—which is currently 8.3% worldwide. These systems make use of a variety of sensors positioned all over the store to keep an eye on product quantities, customer interactions with products, and other internal and external variables that affect inventory levels. This data is analyzed in real-time by an intermediate processing layer, sometimes called the "fog layer," which helps with decision-making and keeps products on the shelves. Furthermore, this idea has been applied to the home, as demonstrated by Amazon's "dash button," which makes it simple for customers to restock on household supplies. Another area where IoT is having a big impact on retail is dynamic pricing. By taking into account variables like shelf life dynamics during production, transportation, and distribution, retailers can apply dynamic pricing mechanisms for fresh produce and groceries. This strategy guarantees that product quality and condition are appropriately reflected in pricing. Nonetheless, difficulties in determining how long products will last on the shelf during the retail phase still need to be resolved. IoT is changing shopping experiences in the area of smart environments and objects. Smart shopping carts improve product promotions and provide a more convenient shopping experience by utilizing technologies such as Bluetooth low energy for tracking and localization. To put it briefly, the retail industry is utilizing IoT technologies to maximize sales revenue, improve customer experiences, and encourage energy efficiency in addition to guaranteeing the freshness and quality of products. The retail industry is changing as a result of this revolutionary journey, which is bringing new revenue streams and increased operational efficiency. The retail industry has exciting prospects for the future that will benefit both customers and businesses as long as retailers continue to embrace IoT (Nukala et al., 2016).

3. Methodology

3.1. Search strategy and study selection

Our review was conducted following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). Eligible studies were identified by conducting a comprehensive keyword search on the Web of Science (WoS) databases in a Boolean operation, i.e., Title, Abstract, Keyword = "food waste" OR "food loss" AND “sensor” AND "dynamic" OR “real-time” OR "internet of things" OR "IoT". We then met our inclusion criteria for the literature search: the original article and review article, written in English and published online from 2003 to 2022. In total, there were 791 articles available on WoS. Subsequently, six hundred and thirty-nine (n=639) records from the literature review database were removed because of being out of the research scope. We further excluded papers (n=81) that have no relation to FLW via real-time IoT-based technology from a life cycle assessment (LCA) perspective by browsing the title and abstracts. In this way, we retrieved 71 papers to explore the role of real-time sensor-based technologies in reducing FLW along the value-added chain.

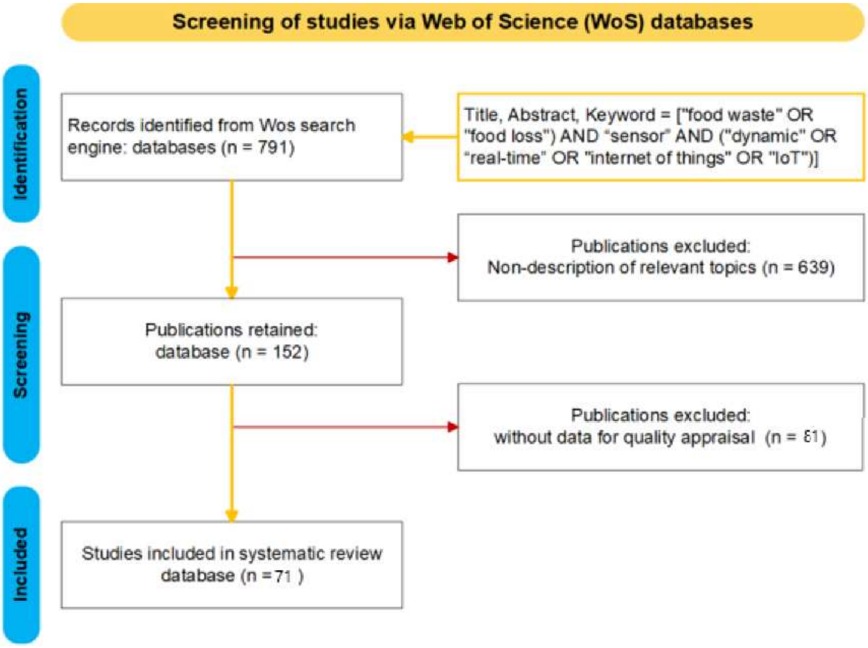

Figure 2: Literature review studies identified and screened from the WoS database

3.2. Quality appraisal

While the exact terminology to describe IoT-related technologies varies under different scenarios, this study highlighted crucial potentials, gaps between previous studies, and future trends by using such technologies in the food supply chain as found in the literature. The application of IoT holds significant promise for revolutionizing food supply chains by offering opportunities for precision, traceability, visibility, and controllability. The exponential growth of IoT-based solutions in reducing FLW also presents a vast potential for generating valuable data in this context. For example, inefficient stock rotation of products with a shorter remaining shelf life can lead to losses in storage or retail stores. As such, innovative IoT-based technologies can facilitate FLW reduction across the entire value-added chain in food systems. We then asked the following three research questions (RQs):

RQ 1: What are the main characteristics of food sectors from "farm-to-fork" in the context of the IoT domain? The answer to this question relied on the implementation and impacts of the IoT-based solution across various food categories, stages, and territories along the value-added chain.

RQ 2: How did different shelf lives and losses of food products evolve by using IoT-based technologies as they traverse the value-added chain, and how did they respond to external factors, such as temperature? We hypothesized that shelf life models initially delineate the alterations in product quality and remaining shelf life encountered during transport or storage and how this data can be utilized to gauge FLW.

RQ 3: Did the implementation of an effective IoT-based monitoring system alleviate some adverse effects stemming from resource utilization while concurrently reducing FLW? Here the challenge was that creating an automated system to monitor FLW requires an integrated approach by considering both positive benefits and rebound effects (e.g., sensor), including their life cycle environmental, economic and social assessment.

3.3. Data extraction and analysis

The relevant articles identified in this review were created from WoS database and then analyzed using Google Sheets. The literature review was conducted based on the inclusion criteria of extending the shelf life of food products to prevent FLW via real-time technologies in the context of the IoT domain from an LCA perspective. Furthermore, this study used VOSviewer version 1.6.19 that offers text mining functionality to construct and visualize co-occurrence networks of important terms extracted from a body of scientific literature. Co-occurrence networks can be generated using data obtained from the WoS, enabling the identification of relationships and interactions among various subject areas. Network visualization includes multidimensional scaling and clustering features, making it a potent method for analyzing diverse bibliometric networks, such as keyword relationships. In network visualization, clusters are color-coded to represent specific node properties. For example, nodes may signify keywords, and node size can indicate the frequency of keyword citations. Terms that co-occur frequently tend to be positioned closely to each other in the visualization.

4. Literature review analysis

4.1. Status quo of IoT technologies in the food supply chain

The retrieved 71 papers used for describing the contribution of IoT technologies to mitigate FLW along the value-added chain can be categorized by years of publication, types of publication, food categories and stages.

Number of articles published between the years of 2003 and 2022 is analysed to identify trends and patterns in articles with the intention of shedding light on the development of research in this field. Figure 3 shows how articles are distributed throughout these two decades. Notably, There were no publications noted until the year of 2008. Thus, this first level highlights the preliminary phases of investigation and study of IoT applications in relation to FLW along food supply chains. Beginning in 2008, there was a noticeable change as publications started to rise. This significant surge from 2014 onwards points to a time of increased research effort and the top of this rising trend, which included 30 articles, was reached in 2022. The discovered patterns show the increasing interest in the use of IoT applications in FLW mitigation along food supply chains. The initial years saw limited interest, possibly due to the nascent nature of IoT technology and its application in the food industry. However, there was a noticeable rise in research production starting in 2014, demonstrating a greater understanding of the potential advantages of IoT in reducing FLW within the food supply chain.

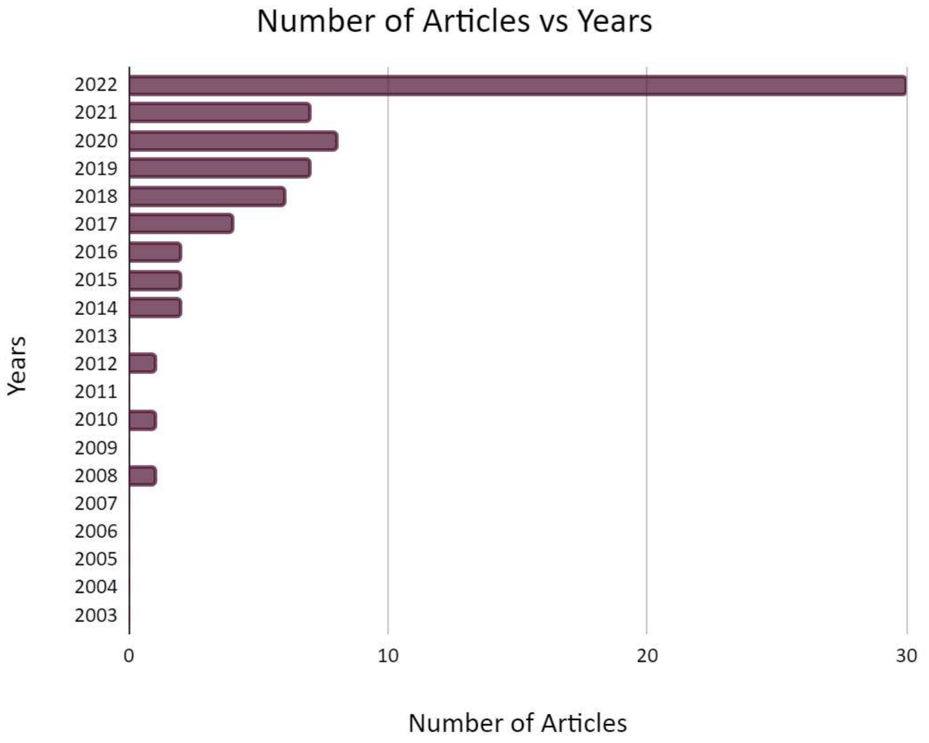

Figure 3. Number of publications spanning from 2003 to 2022

Figure 4 demonstrates number publications on IoT in reducing FLW along food supply chains published in different journals. With seven articles in the lead, "Sensors" highlights its crucial function while with six articles, "Food Control" follows immediately. The journal "Foods" makes a strong showing with four articles. Moreover, two publications from each of many other journals which are "Comput. Electron. Agric.," "Comput. & Ind. Engineering," "Food Chemistry," "Food Hydrocolloids," "Food Packag. Shelf Life," "IEEE Access," "J. Food Eng.," "J. of Cleaner Production," "Procedia Comput. Sci.," and "Sustainability," are included. The interest in IoT applications in reducing food supply chains worldwide is reflected in a variety of other journals and this variety highlights the need of multidisciplinary collaboration.

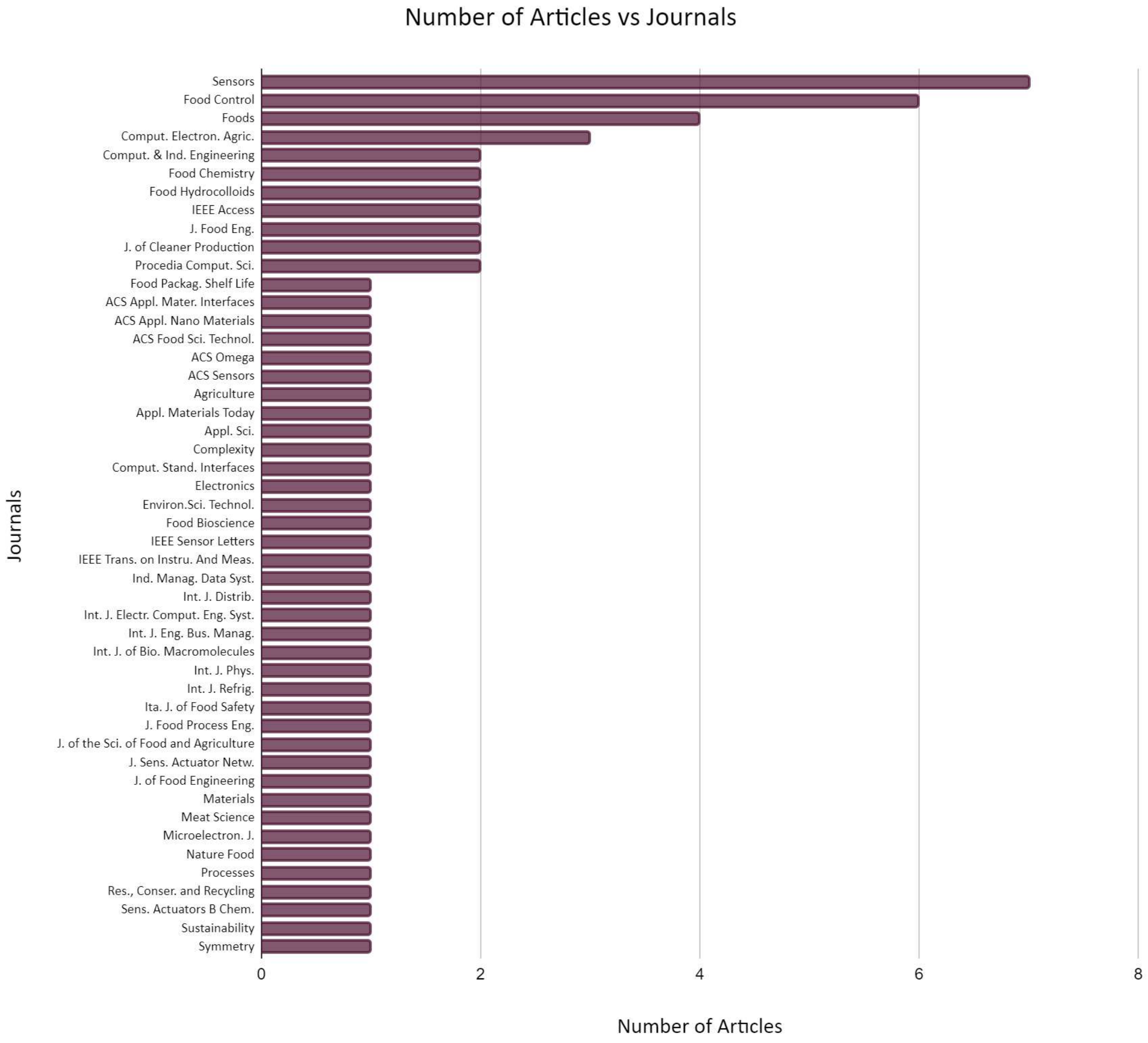

Figure 4. Number of publications in different types of journals

Figure 5 shows the percentage of articles based on different food groups. With 25,4%, papers devoted to examining IoT applications in mitigating FLW across multiple food groups, evaluating more than one food group in each study appears to be a popular choice. 16.9% of papers examine fruits which come in second place in terms of research concentration while with 15.5% of publications, meat and fish appear as other significant food categories. This indicates a considerable interest in utilizing IoT to improve the resilience of the fruit, meat and fish supply chain. Vegetables, with 8.5% of articles, represent another important focus group. Furthermore, smaller numbers of entries for Cereals, N/A (representing unidentified food categories), Beverages, Composite Dishes, roots, tubers, plantains, and spices and condiments also exist. This reveals that focus on non-perishable food groups are less than perishables while revealing the adaptability of IoT technology in reducing FLW across different food supply chains simultaneously.

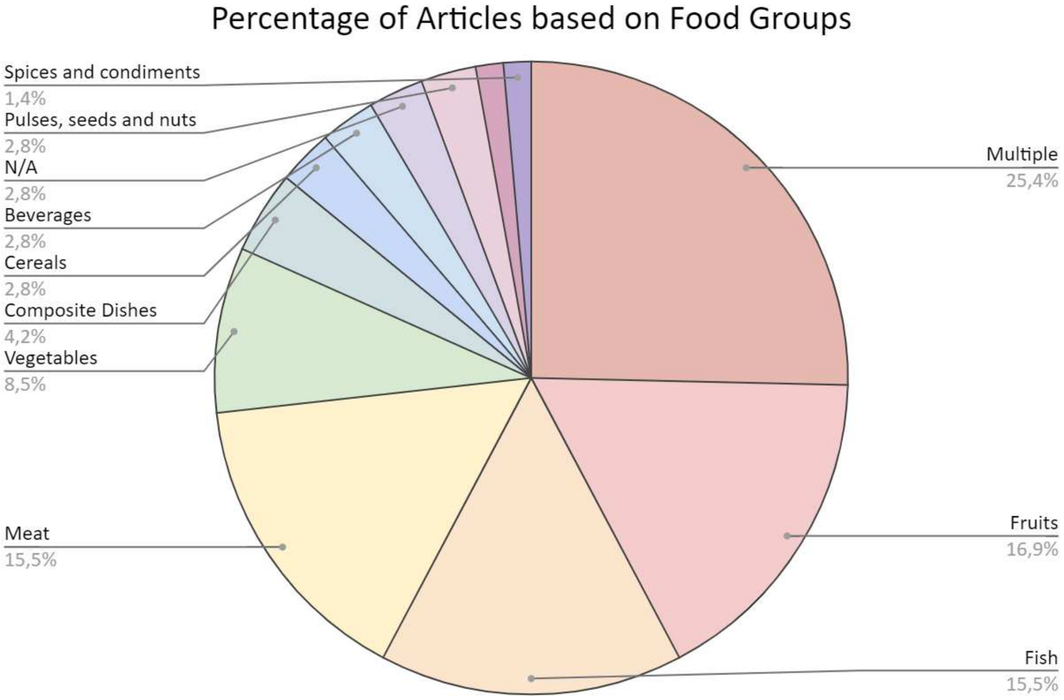

Figure 5. Share of publications in various food groups

Figure 6 illustrates the percentage of articles based on food supply chain stages. Storage with 39,4% dominates the area of research and transportation follows at 19,7%, highlighting tracking and monitoring during transit. Storage and distribution accounts for 14.1% indicated another important food supply chain stage. Moreover, retail at 7% and manufacturing at 5% follow the other, while multiple stages are focused on 12.7% of the articles. Also 1 article focusing on storage at customer level was found. This variability highlights the potential of using IoT for reducing FLW in all stages of the food supply chain.

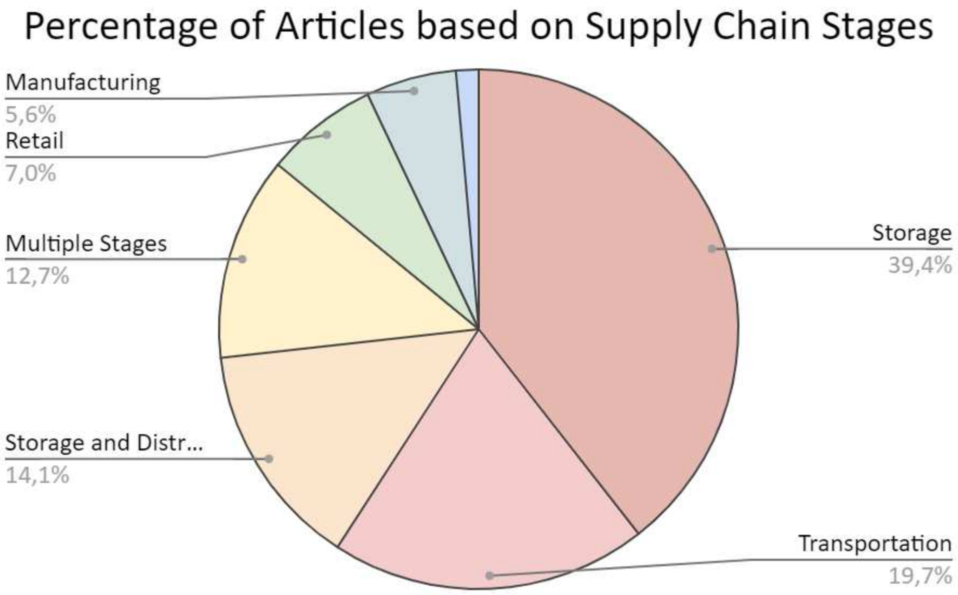

Figure 6. Share of publications in different supply chain stages

Figure 7 illustrates the distribution of articles related to IoT applications in mitigating FLW along food supply chains across various countries revealing the global interest and engagement of researchers. With a total of 19 articles, China takes the lead in the research. This outstanding contribution demonstrates China's initiative in IoT research in the context of FLW prevention and mitigation along food supply chains. The "Multiple Countries" category includes research that exhibits cross-national cooperation. Moreover, 5 articles each from Italy and Spain show a rising interest in using IoT to reduce FLW along food supply chains in Europe while South Korea represents the growing interest in IoT among Asian countries and 4 articles are also presented by the United States. Furthermore, various nations, including Brazil, Hong Kong, India, Iran, Portugal, Turkey, have also contributed one to three articles. These contributions demonstrate a widespread interest in examining the possibilities of IoT technology in the food business, demonstrating the technology's adaptability in tackling a range of food supply chain concerns.

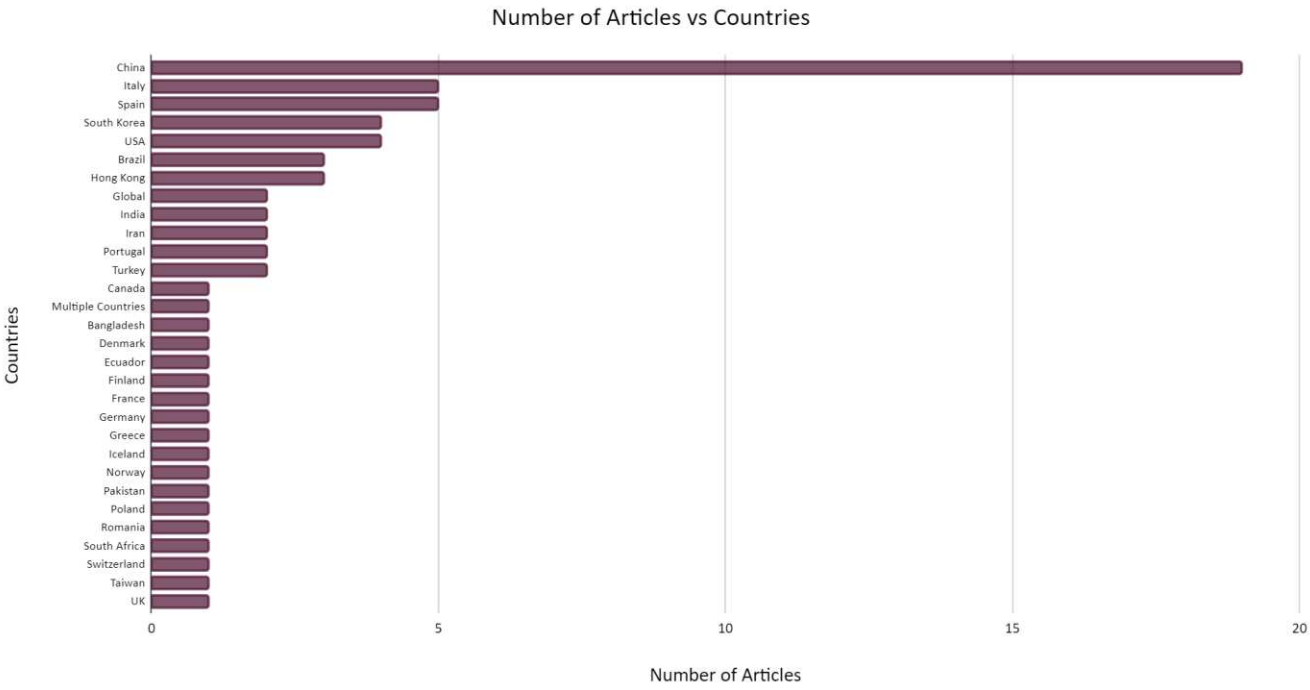

Figure 7. Numbers of publications showing IoT technologies to mitigate FLW spanning from 2003 to 2022 in different countries.

Moreover, Figure 8 illustrates the numbers of publications from 2003 to 2022 in different countries on a worldwide basis on the world map. It is clearly seen here that China stands out in the studies.

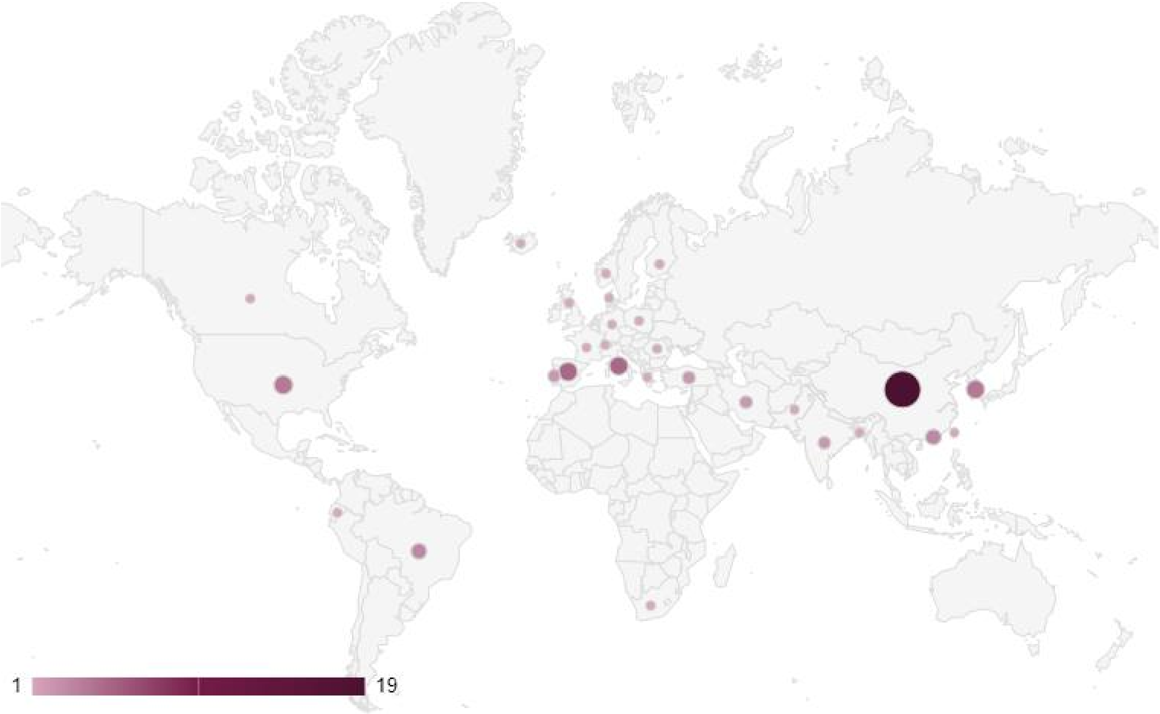

Figure 8. Numbers of publications on a worldwide basis on the world map.

4.2. In-depth analysis of the potential using IoT technologies to reduce FLW

Within the collected papers, our literature review rigorously examines the opportunities and challenges associated with the utilization of IoT technologies for the purpose of mitigating and preventing FLW throughout the various segments of the food supply chain. This comprehensive analysis encompasses the entire spectrum of the food system, including production & manufacturing, storage, transportation, distribution centers, retail, and other pertinent stages.

Furthermore, our review meticulously categorizes these papers across several dimensions, including food categories/products, geographical regions, technological domains/methodologies, product shelf life, FLW considerations, and a LCA perspective that accounts for environmental, economic, and social dimensions. This systematic categorization serves to provide an academically robust and holistic overview of the ongoing developments in the deployment of IoT technology in the realm of food waste management, with the overarching objective of facilitating the establishment of an affordable and accessible smart food system.

4.2.1. Production and manufacturing stage

The food industry is experiencing unprecedented demand for automation and digitalization, particularly in light of the COVID-19 pandemic and Russia-Ukraine conflict. Using the innovations of Industry 4.0, the fourth industrial revolution, the "Food Processing 4.0" concept has emerged as a potent response to this demand. This strategy entails integrating contemporary digital technologies into food processing operations, such as robotics, smart sensors, artificial intelligence (AI), the Internet of Things (IoT), and big data (BD). Adopting Food Processing 4.0 has many benefits, the main ones being the enhancement of food safety, the reduction of food waste, the improvement of food quality, and the mitigation of the food processing industry's negative environmental effects. These developments are in line with the global "Green Shift" in the industry and greatly contribute to a more ecologically friendly and sustainable method of food processing. It is becoming more and more common to integrate different kinds of robots into food processing operations. The COVID-19 pandemic brought to light how crucial automation and robotics are to reducing the labor shortage and maintaining business continuity in the food sector. However, historically, the use of robots in this industry has been constrained by issues relating to the variability in the size and shape of food products. Robots' potential applications have expanded due to recent technological advancements, such as the development of sophisticated gripper designs that allow them to handle delicate or irregularly shaped food items. Smart sensors are essential for ensuring the safety and quality of food. They can be electronic or spectroscopic in nature. The application of smart sensors in food packaging has the potential to improve food quality and safety while giving consumers useful information. The trend of sensors becoming smaller and more portable is noteworthy, as it is fueled by developments in areas like nanobiotechnology. Thanks to this trend, food processing professionals and a wider range of consumers can now access efficient and affordable smartphone-based sensors. In the food processing sector, artificial intelligence (AI) is a game-changer, capable of handling difficult problems and carrying out a wide range of functions. AI is already transforming a number of industries, including process optimization, quality and safety inspections, and food sorting. In the near future, it is anticipated that the application of AI to food processing will spread to a number of other areas, propelling the sector's advancement toward intelligent food processing. The Internet of Things (IoT) and associated technologies are being progressively adopted by the food processing sector. IoT has the potential to lower food waste and production costs while improving food quality, safety, and logistics. IoT-enabled real-time tracking and monitoring of food production, distribution, and storage can improve operational efficiency and supply chain transparency. IoT has the potential to revolutionize the food processing industry and other related fields, even though there are still certain operational, financial, regulatory, and technical issues that need to be resolved. Another component of Food Processing 4.0, which is poised to completely transform the food business, is Big Data (BD). There are many advantages to using data analytics tools, such as better food safety, demand forecasting, real-time decision-making, and efficient food waste management. To fully realize the potential of BD in food production, however, a number of obstacles must be overcome, including a lack of system standards, restricted data sharing, worries about data security, and legal issues. The food industry is seeing a rise in the use of novel food processing technologies like Pulsed Electric Field (PEF) and High-Pressure Processing (HPP). These technologies provide resource conservation, time savings, and energy efficiency—all of which are in line with Industry 4.0 principles (Hassoun et al., 2023).

Through the literature review, 4 articles specifically focusing on the production/manufacturing stage of the food supply chain have been found. These articles revealed the potential of using wireless sensor systems for a variety of food categories, including rice farming, bread-making, spice drying, and water quality. Two of these articles belong to Italy making it a leading country in terms of conducting research for the production and manufacturing stage. However, the low total number of articles shows that this stage is not a priority.

Baire et al. (2019) investigated environmental factors in bread-making, a subset of cereal processing. They found significant variations in temperature and humidity across different stages. The average daily air temperature was 19.32 ± 1.033°C, deviating notably from the recommended 28°C during kneading and early leavening. In contrast, the leavening room temperature was 28.62 ± 1.74°C. Relative humidity averaged 59.98% ± 6.10% in the kneading room and 61.26% ± 12.82% in the leavening room, both significantly above recommended levels. The study also recorded fluctuations in carbon dioxide (CO_2) and carbon monoxide (CO) concentrations between January and August. These findings enhance our understanding of environmental conditions in bread production, influencing both process optimization and product quality. However, while the data is crucial for bread production, the study did not translate these findings into numerical outcomes for FLW mitigation and environmental perspectives. Catania et al. (2020) examined the drying techniques for aromatic herbs, specifically Sage and Laurel, using a wireless sensor system. The study found distinct microbiological stability between the two, with Sage exhibiting a longer shelf life than Laurel. This was corroborated by water activity measurements indicating moisture content of less than 14% for Sage and 32% for Laurel. Despite comparing the shelf lives based on moisture content, the study did not provide clear numerical values for their actual shelf lives. Besides, Zheng et al. (2021) studied beverage production, specifically water, using ZigBee wireless sensor technology. Their research assessed microbial concentrations, revealing variations in levels of flora (0.30-0.35), fungus (0.10-0.20), germs (0.23-0.32), and bacteria (0.10-0.20). These findings highlight disparities in microbial composition in the water samples. Although the data is crucial for understanding water quality, the study did not translate the findings into numerical outcomes related to FLW, shelf-life, or environmental impact. Additionally, Siddiqui et al. (2021) explored sustainable rice farming in Bangladesh using a wireless sensor system. Their innovative approach indicated a potential 90.91% reduction in water usage compared to traditional clay canal methods. This suggests considerable water savings, especially vital for regions like Bangladesh. The proposed system also anticipated enhanced energy efficiency, resulting in a smaller energy footprint than conventional methods reliant on continuous watering. The adoption of an AWD (Alternate Wetting and Drying) automation scheme is expected to lower irrigation costs, and the transition to plastic pipes should further reduce costs and environmental impact. These advancements herald a more sustainable and economically viable rice farming future in Bangladesh. However, the study did not address FLW in this context.

Wireless sensor systems offer significant potential for enhancing sustainability in food production. However, a comprehensive evaluation of their impact on food loss reduction, shelf-life extension, and detailed environmental implications remains pending. This underscores the need for additional research to harness the full benefits of wireless sensor systems in food production and manufacturing management.

4.2.2. Storage stage

In modern food preservation and storage, digital technologies play a pivotal role in ensuring the quality and safety of a vast range of food products. Since warehouses act as central locations for the storage of processed food goods, warehouse management is an essential component of the food industry. These facilities frequently hold a wide variety of goods, and prompt customer service while maintaining the quality and safety of food products that have been stored depends on effective and optimal management. For warehouse management, utilizing Internet of Things (IoT) technology is revolutionary in a number of ways. First, in the warehouse, IoT technology helps with product identification. Warehouse managers must be well-versed in every product that is intended for distribution. RFID (Radio Frequency Identification) technologies, among other Internet of Things technologies, are essential to this. They make it possible to precisely identify and monitor the food products that are currently in the warehouse. By ensuring that every item is accounted for, this technology lowers the possibility of mistakes or oversights when managing inventory. Second, warehouse management is given the ability to keep an eye on the state of the food products kept in the facility thanks to IoT technology. When anomalous circumstances occur, such as improper temperatures, improper product placements, or running low on product stocks, it offers real-time information. Warehouse management can maintain the quality and safety of food products by using sensors and other perceptual technologies, such as voice and video monitoring, to quickly identify and address any issues. Improving traceability is essential to improving warehouse management skills. The capacity to track and identify goods inside a warehouse is known as traceability, and it heavily depends on IoT technology. For example, the use of RFID tags facilitates the tracking, identification, and collection of data from food items. In addition, data collected via RFID is monitored and sent to internet cloud services via network gateways with the help of Wireless Sensor Networks and actuators. These cloud services provide a comprehensive and easily accessible resource for warehouse management by acting as repositories for food product data inside the warehouse. As a result of its ability to monitor conditions, improve traceability, and improve product identification, Internet of Things technology is revolutionizing warehouse management in the food industry. A more effective and efficient system is produced by integrating different IoT components, guaranteeing that food products are distributed, managed, and stored precisely and in compliance with quality and safety regulations. Modern food supply chain management is leading the way with the use of warehouse management systems that have been enhanced with IoT capabilities (Maulana et al., 2021)

From the public literature reviewed, 28 studies addressing storage across diverse food categories—including cereals, fruits, vegetables, meats, and seafood—highlight advances made using smart packaging, wireless sensor systems, and other cutting-edge tools. These research delve into the complexities affecting food preservation, exploring tools like RFID, wireless sensor networks (WSN), IoT sensors, and blockchain systems. Their focus is on understanding how environmental factors, such as temperature, humidity, and gas concentrations, influence food quality during storage. The findings from these studies elucidate optimal conditions for food preservation, reducing FLW, and ensuring food safety.

Badia-Melis et al. (2015) investigated food storage dynamics, focusing on citric fruits and various nuts. By integrating RFID and WSN systems, they assessed environmental factors within storage facilities. Notably, they detected significant temperature variations between day and night cycles, approximately 5°C, more pronounced outside the storage facility with a 3°C change. Humidity analysis revealed consistency at lower levels, with both outer and inner nodes averaging around 4 kg of water/kg of dry air. However, at higher humidity levels, the exterior recorded above 12 kg water/kg dry air, while the interior remained below 8 kg. Furthermore, relative humidity outside remained below 55%, but the storage room occasionally peaked at 80%. These findings underscore the challenges in achieving optimal storage conditions for diverse foods.

Y. Tsang et al. (2017) used a WSN system to monitor storage conditions for a range of products. Their findings indicated that a decrease of around 2°C in temperature and a 10% increase in humidity maintained optimal conditions for environmentally sensitive products (ESPs) over 10 days, leading to a notable 10.4% reduction in energy consumption. Most importantly, performance metrics improved: product obsolescence for ESPs reduced from 13% to 8%, customer complaints decreased from 8% to 2%, and both order fulfillment and satisfaction rates increased by 5.45% and 17.33%, respectively. These results highlight the significance of meticulous environmental control in ensuring product quality.

Tervonen (2018) investigated the storage of seed potatoes using a WSN system. Over a span of seventy-one days, temperatures within the storage ranged from -5°C to 5°C, while relative humidity varied between 50% and 96%. Such fluctuations in temperature and humidity are crucial to monitor, given their significant impact on the preservation and quality of seed potatoes. The study emphasizes the importance of precise monitoring and control over the fluctuating environmental conditions seed potatoes experience during storage.

De Venuto and Mezzina (2018) explored the use of a WSN system in the storage of tomatoes. The estimated shelf life of tomatoes on each pallet increased by approximately 1.2 ± 0.5 days in a non-refrigerated environment, representing nearly 15% of the product's maximum usable life. This observation was made over a period of roughly ten days and eleven hours. The study underscores the potential of precise monitoring in non-refrigerated conditions to prolong the shelf life and enhance the quality of tomatoes, which can significantly influence the tomato supply chain and ensure consumers have access to fresher produce.

Popa et al. (2019) utilized a WSN system within a vacuum container to observe onion sample behavior in Romania. In a reference experiment with an empty container, the gas sensor output quickly peaked at 3 V. However, when the MQ5 gas sensor was introduced into the container filled with onion samples, its output exhibited considerable fluctuations for the initial 2 hours before stabilizing around 1 V. This consistency suggests the MQ5 sensor likely detected volatile organic compounds, specifically alcohol and carbon monoxide (CO), markers of onion deterioration. Meanwhile, humidity in the onion-filled container increased by approximately 30% over a 5-hour experiment at 27°C. This study offers insights into the vapors onions emit during storage, enhancing our understanding of onion degradation, related gas emissions, and the potential of WSN in tracking these changes.

Tsang et al. (2019) utilized a blockchain-IoT-based food traceability system to monitor the quality deterioration of various perishable foods during storage. Their findings revealed diverse degradation rates across the food categories studied.

- Food Type 1 experienced a rapid quality decline, with its normalized quality dropping nearly 90% in just four days.

- Food Type 2 demonstrated a more gradual degradation, taking 65 days to decrease by 90%.
- Food Type 3's quality diminished even more slowly, requiring 90 days to decline by 90%.
- Remarkably, Food Types 4 and 5 showed exceptional stability, maintaining over 90% of their normalized quality even after 100 days of storage.

However, the specific identities of these food types were not disclosed in the study.

Jilani et al. (2019) conducted a study of broiler carcass storage, focusing on distinguishing between low-quality PSE (Pale, Soft, Exudative) meat and normal meat. They used a microwave sensing technology-based WSN system to detect differences in meat quality. Notably, PSE meat exhibited a steeper pH decline, from 6.8 to 5.7, compared to a decrease from 6.9 to 5.9 in normal meat over 1 to 8 hours. Colorimetric analysis showed that normal meat had higher levels of brightness, yellowness, and redness, pointing to visual quality differences. Dielectric studies further differentiated PSE from normal meat, with significant discrepancies in their resonance frequencies indicative of distinct dielectric properties. These findings underscore the potential of advanced sensing technologies to classify meat quality effectively.

Banga et al. (2019) used an insect detection probe to investigate the storage of chickpeas and green grams in India, focusing on insect infestation detection. They found that chickpeas infested with C. maculatus and C. chinensis had average relative humidity and temperature readings of 40.60% and 27.59°C, and 54.64% and 27.10°C, respectively, compared to the surrounding environment's 68% RH and 30°C. For green grams, ambient RH and temperature were 60% and 37°C, while infested conditions showed 33.20% RH and temperatures of 26.86°C and 27.16°C. The chickpeas' texture and higher RH contributed to a greater sound attenuation, resulting in lower sound amplitude compared to the smoother surface of green grams. This study provides insights into the acoustic monitoring of stored legumes affected by insect infestations.

Feng et al. (2020) investigated salmon storage using an electronic nose (e-nose), focusing on assessing freshness and quality over time. The research was carried out in China and involved an experimental investigation. Temperature and humidity variation was as follows: The storage conditions for salmon were characterized by temperature and humidity fluctuations. The ambient temperature varied from -1.9°C to 1.6°C while humidity ranged from 26.2% to 34.3% (when set temperature = 0°C). The temperature changes ranged from about 2.8°C to 5.9°C, with humidity ranging from about 27.4% to 32.6% (when set temperature = 4°C). Finally, the temperature variations ranged from about 4.8°C to 7.7°C, while humidity fluctuated between about 25.4% to 31.7% (when set temperature = 6°C). Also, texture profile analysis (TPA) was conducted to see several key changes in these textural characteristics under different temperature conditions. Hardness parameter revealed that at 4°C, the meat's hardness significantly changed during the first 9 days, potentially indicating a decline in its quality or texture while chewiness parameter showed that after 3 days at 4°C and 14 days at both 0°C and 6°C, the meat became notably more or less chewy, suggesting texture changes. Springiness, cohesiveness, and gumminess parameters demonstrated that significant changes occurred after 3 days at both 0°C and 4°C, reflecting shifts in the meat's elasticity, stickiness, and gummy quality and resilience parameter revealed notable changes in the meat's ability to recover its original shape after 3 days at both 0°C and 4°C, indicating shifts in its response to external forces. These findings collectively indicate that the textural attributes of salmon meat are sensitive to temperature and storage conditions. The observed changes in hardness, chewiness, springiness, cohesiveness, gumminess, and resilience parameters at different temperatures highlight the importance of precise storage conditions to maintain the desired textural qualities of the meat, ultimately impacting its quality and consumer acceptability. Moreover, pH variations were observed and the study found that pH values exhibited a consistent trend, where they decreased during the initial 3 days of storage and then increased after this period. Lastly, it has been detected that the sensory properties of all salmon samples were satisfactory during the first 3 days of storage. However, after this initial period, significant differences in the overall acceptance of salmon samples were observed, suggesting a notable change in sensory quality. This research provided valuable insights into the impact of different storage conditions on salmon quality, texture, and sensory properties, with implications for maintaining and ensuring the quality of this popular seafood product.

Using a blockchain-based wireless sensor system to track environmental parameters, Feng et al. (2020) investigated the shellfish storage. The study documented a gradual weight loss in the stored samples, ranging from an initial 0.12% to 0.40% after 80 hours at -18°C, indicating moisture loss over time and temperature fluctuations were also observed, with variations spanning from approximately -23.2°C to -20.1°C during the cold storage period. In contrast, humidity levels exhibited a rising trend throughout storage. In addition, there were notable alterations in the gas concentrations within the storage environment. Specifically, CO2 concentrations saw a rapid spike from their initial level of 178.13 ppm to an accumulated 6965.62 ppm, while O2 levels increased to 32.37%. These results highlight how dynamic shellfish storage is and the incorporation of a blockchain-driven wireless sensor system enhances transparency and data integrity.

Sharif et al. (2021) investigated the UK's spring water storage practices by using machine learning and radio frequency identification (RFID) technology to track food contamination and contents in water bottles. With an accuracy of 90% in detecting food contamination and contents, even in water bottles with different amounts of salt and sugar, their research produced impressive findings. These results highlight the potential of RFID and machine learning as an effective tool for guaranteeing the safety and quality of bottled drinks, aligning with quality control requirements and customer trust in the bottled water market in the UK.

Nair et al. (2021) used an electronic nose (E-nose) for olfactory analysis in their investigation on banana storage practices in India. The work appears to entail a sizable dataset, comprising 3000 samples over the course of 2 days, despite the lack of explicit experimental information. The dataset comprises four characteristics: the input features include gas concentration (measured in parts per million), temperature, and humidity values. Meanwhile, overripe/ripeness represents the target value that the proposed model aims to forecast. The data that was recorded concerned variations in the concentration of gas, which ranged from 0.083 to 1.0 parts per million (ppm). Over time, the value of gas concentration shows a non-constant trend as it climbs steadily. Temperature and humidity, on the other hand, follow a stable and cyclical pattern that varies within a predetermined range of values. Notably, the gas concentration value grows exponentially when it crosses a threshold, which corresponds to an increase in releases of ethylene gas when the fruit starts to ripen. Using a dataset gathered from bananas, gas levels, in particular ethylene, were measured and recorded at different ripening stages. Data cleaning techniques were effectively used after data gathering. Machine learning techniques were then used to process the data and derive insightful information on ripening phases and expiration dates. These results show that this affordable e-nose has the ability to precisely detect product expiration dates and minimize food waste when combined with powerful machine learning algorithms.

Giarratana et al. (2022) investigated the Atlantic mackerel storage using a mathematical model to assess the impact of temperature dynamics on spoilage, determined by a critical sensory decline at a bacterial load of 6 Log cfu/g. The study found that under constant temperatures of 1±0.5°C, the critical spoilage threshold was reached after 9 days, while variable temperatures between 1°C and 7°C led to spoilage after only 3 days. It can be concluded from the results that 6 days (66.7%) of shelf-life extension is possible when careful temperature control is provided. This emphasizes the importance of stringent temperature control in seafood storage for ensuring food safety and quality.

Makarichian et al. (2022) utilized an electronic nose (E-nose) for assessing garlic preservation in Iran, introducing the decay severity index (DSI) as a metric for freshness evaluation. The study indicated that by the 8 day, it was possible to distinguish between healthy and infected garlic samples with high accuracy. The study also suggested that spoilage in garlic stored in low-density polyethylene (LDPE) bags at room temperature could be detected as early as the fourth day within a 28-day period. These findings highlight the effectiveness of the DSI and E-nose in enhancing garlic quality control and early spoilage detection.

Waimin et al. (2022) examined chicken storage in the U.S. using WSN for prompt and precise spoilage detection. The study confirmed the effectiveness of sensor tags in identifying spoilage in deliberately adulterated samples, with the tags detecting radio frequency peak changes exceeding a 20% threshold within 4 days. The tags also proved stable with fresh samples, showing only about a 5% shift after 10 days.

Leite et al. (2022) investigated the efficacy of smart packaging technologies with various modified atmosphere gas mixtures (MO: BP) in detecting early spoilage in strawberries, salmon, and beef. At a 1% MO: BP ratio, spoilage detection was delayed, with salmon and beef showing signs after three days and strawberries after ten days. Conversely, a higher MO: BP ratio of 2% allowed for quicker response to spoilage, with noticeable changes in color within 24 hours, underscoring the potential of smart packaging to enhance food quality management and reduce waste.

Kondjoyan et al. (2022) used both experimental data and mathematical models to explore the influence of temperature and oxygen levels on beef color changes. The study found that maintaining 100% oxygen in the storage environment delayed the color change, thereby extending the beef's shelf life by up to 3 days, particularly at a temperature of 2°C. This effect persisted even at elevated temperatures of 10°C, with the shelf life extension (up to 6 days) being more pronounced at this higher temperature. The research further highlighted the critical role of temperature and oxygen in preserving meat color, showing that lower temperatures increased the lag phase before color changes, and that increasing oxygen from 20% to 100% significantly influenced the rate of color change.

Yang et al. (2022) used smart packaging technologies to monitor freshness of shrimp during storage in China. The study found that the packaging label's color transition from brick red to orange-red indicated shrimp spoilage after one day at 25°C and three days at 4°C. However, the label's color remained consistent when the shrimp were stored at -20°C for five days, suggesting maintained freshness. These visual changes were corroborated by total volatile basic nitrogen (TVB-N) measurements, validating the smart packaging system's effectiveness in real-time freshness assessment, and highlighting its potential to inform consumers about seafood quality.

Alexi et al. (2022) utilized a cadaverine biosensor to assess the quality of pork cutlets in Denmark, discovering a significant correlation between microbial analyses and sensory evaluations of freshness. Their findings suggest that under modified atmosphere packaging (MAP) at 5°C, pork cutlets could have an extended shelf life of 2 to 3 days (between 22.2% and 33.3%, with the average value of 27.8%) beyond the standard 9 days.

Si et al. (2022) investigated the impact of smart packaging on shrimp storage in China, revealing that shrimp quality deteriorated significantly after only three days at 20°C, rendering it unfit for consumption. This study underscores the crucial role of temperature control and smart packaging in preserving the quality and safety of seafood products.

Ai et al. (2022) focused on pork preservation in China using smart packaging technologies, identifying key safety and freshness indicators. The study found that after 6 days at 4°C, pork exhibited elevated pH and total aerobic bacterial count (TABC) levels, indicating spoilage due to bacterial activity and acidity changes. Additionally, the total volatile basic nitrogen (TVB-N) values, indicative of meat spoilage, peaked after 4 days. The smart packaging's RPP10 film lightened in color, visually signaling the loss of freshness. These findings underscore the importance of smart packaging for real-time quality control in China, where pork is a dietary mainstay, thereby enhancing consumer trust and the quality of meat products.

Lei et al. (2022) utilized smart packaging technology to assess the freshness and quality of shrimp stored at various temperatures, discovering a pronounced correlation between the shrimp's color and the storage temperature. Shrimp stored at 25°C turned from gray to bright red within 36 hours, signaling potential degradation in freshness and quality from temperature effects. In contrast, shrimp maintained at 4°C for 72 hours showed no notable color change, emphasizing the critical role of refrigeration in preserving the color and quality of shrimp.

Teixeira et al. (2022) examined the storage of gray shrimp in Brazil, employing smart packaging technologies to manage seafood quality and freshness. The key finding was the significant color change of shrimp after 60 hours of storage at controlled conditions (6°C ± 2°C temperature and 60% ± 5% relative humidity). This change was monitored using colorimetric markers made from an anthocyanin extract on a cellulose acetate base, plasticized with glycerol (GLY) or triethyl citrate (TEC). The color shift served as an indicator of the shrimp's changing freshness and quality.

Jung et al. (2022) leveraed IoT sensors to gather data on perishable food storage by studying dairy (milk) and meat (pork) preservation in South Korea. The study found temperature to be a pivotal factor in product quality, with pork remaining fresh after 63 hours at 4°C, but showing spoilage signs at 37°C. Similarly, milk retained freshness for 140 hours at 4°C but spoiled at higher temperatures. Yet, the final results failed to give a specific date on the product’s shelf life as temperature rose. These findings underscore the critical role of IoT sensors in real-time monitoring and temperature management to ensure food safety, reduce food loss and waste, and enhance consumer confidence in food integrity.

Ma et al. (2022) focused on chicken breast storage in the US, utilizing smart packaging integrated with deep learning to track quality and safety. The key finding was an increase in total volatile basic nitrogen (TVB-N), a freshness and safety indicator, after 96 hours at 4°C, signaling potential quality decline. This highlights the efficacy of combining smart packaging with real-time data analysis through deep learning to proactively monitor the integrity of stored chicken products.

Kilic et al. (2022) examined chicken preservation in Turkey, employing smart packaging and a smartphone app to oversee product quality and safety. The study pinpointed a significant rise in the total viable count, a key microbial load indicator, during storage at 4°C, hitting critical levels after 7 days. This underscores the pivotal role of technology in real-time monitoring and intelligent packaging to ensure the microbiological safety and freshness of stored chicken, potentially mitigating food safety issues.

Marangon et al. (2022) explored fish storage in Brazil, utilizing smart packaging technology to track the shelf life and quality of fish in controlled storage. A pronounced pH shift from 6.5 to 8.0 over 72 hours served as a critical indicator of freshness and quality, reflecting the microbiological and chemical changes occurring. The packaging film responded to the pH change by altering color from a dull light yellow to a bright orange, offering a visual cue of the fish's condition. This study demonstrates the potential of smart packaging to enhance consumer trust, reduce food waste, and streamline quality control in the fish industry by visually communicating product freshness.

The study by Pounds et al. (2022) examined pork preservation in the US, employing smart packaging technology to understand shelf life under different temperatures. It was found that pork spoiled in about 16 hours at 20°C but lasted approximately 28 hours at a cooler 4°C, underscoring temperature's importance in meat preservation. The study also identified a pH range of 5.5 to 5.8 as an indicator of meat spoilage, demonstrating the significance of pH monitoring.

The wide range of research included in this compilation emphasizes how technology has revolutionized methods for storing and preserving food. All of these research have explored the complexities of food preservation in great detail, providing important information on environmental conditions, spoiling markers, and product shelf lives. The findings have broad ramifications for the food sector, empowering interested parties to decide in a way that would improve food safety and quality. These investigations clear the path for a more effective and sustainable method of food storage, from the discoveries on how temperature variations impact the freshness of fruits and cereals to the revolutionary possibilities of smart packaging technology. They provide a road map for extending shelf life, cutting FLW, and enhancing food safety. With our continued use of these technical developments, food storage and preservation have a bright future. In the end, producers, distributors, and consumers all gain from a more sustainable and effective food supply chain thanks to the information and understanding gained from these research. A future where food is plentiful, reliably fresh, and safe is becoming closer by harnessing the power of innovation and data-driven insights.

4.2.3. Transportation stage

Temperature control, hygiene and pest control, traceability, goods management (including handling, damage prevention, and safety), vehicle/container preventive maintenance, and employee management (involving goods handling, personal hygiene, safety protocols, policies, and training) are just a few of the critical issues that arise when transporting food products. Using the Internet of Things (IoT) in the food supply chain (FSC) offers a complete tracking and monitoring solution for all food transportation-related activities. Radio Frequency Identification is a crucial technology in the implementation of IoT for food product tracking within the FSC (RFID). Specific and important information about the food products being transported can be stored in RFID tags and effectively communicated over a wireless network. Real-time alerts and responses are made possible by this technology, especially in situations involving food recalls or safety concerns, allowing impacted products to be quarantined as soon as possible. Furthermore, inexpensive wireless remote systems are used to establish wireless networks inside food transport vehicles, enabling ongoing food safety monitoring while in transit. Real-time monitoring and documentation of various conditions, including temperature, is made possible for FSC stakeholders by IoT systems that are integrated with Hazard Analysis Critical Control Points (HACCP) processes. This guarantees both local and international regulatory compliance and efficient cold chain management. Transport vehicles for food are outfitted with wireless systems that range in complexity, offering real-time access to vital information and connectivity. Numerous vehicular sensing applications and connectivity problems are covered, along with suggestions for improving network security and transportation safety via ideas like Vehicular Ad-Hoc Sensor Networks and the Cognitive Internet of Vehicles (CIoV). Because transportation is so important to the food industry's supply chain, these Internet of Things applications have a particularly big impact there. Food haulage trucks have sensors that allow them to track where they are, keep an eye on temperature, manage inventory, maintain security, determine what needs to be maintained, and change their routes when traffic patterns change. IoT technology allows for the seamless integration and control of these sensors. It is crucial to classify Internet of Things applications in the transportation sector into supply and demand categories. Storage facilities, the transportation network (roads, sea, and air), and the mode of transportation (trucks, ships, or airplanes) are all considered supply-related components. The goods that must be transported and the intended consumers who will receive the goods, on the other hand, are demand-related components. This classification facilitates the efficient and secure flow of goods throughout the food supply chain by streamlining and optimizing IoT applications for food product transportation (Jagtap et al., 2021).

The literature review revealed 14 articles specifically focusing on the transportation stage. In the dynamic landscape of food transportation, the studies discussed in this compilation provide invaluable insights that have far-reaching implications. From the transportation of perishable food items like cod fish and bananas, to the use of cutting-edge technology such as IoT sensors and digital twin technology, the findings highlight the crucial role of temperature, humidity, and other environmental factors in maintaining the quality and safety of goods during transit.

A study by Wang et al. (2010) on the transport of perishable food products exemplifies how mathematical modeling and strategic planning can significantly enhance supply chain efficiency and product safety. By devising a set of guidelines for optimizing truck and container schedules, the study successfully demonstrated a substantial reduction in transportation losses, particularly in a scenario simulating an accident where losses were cut by half. This shows the value of employing calculated rule-based rescheduling procedures and risk mitigation techniques to ensure better quality control and safety of food products during transit.

The study by Hafliðason et al. (2012) on cod fish transportation offers vital insights into the impact of temperature variations on seafood shelf life. Findings indicated that maintaining a stable temperature around 0°C is critical for preserving cod fish during transit. The mistreated pallet (P2) experienced an average temperature 0.7°C higher than the properly maintained pallet (P1), resulting in a one-day loss of shelf life for the cod fish—a significant impact given the short shelf life of fresh seafood. Further observations revealed substantial temperature fluctuations within the transportation container, with the most extreme variation reaching 18°C, and an overall average difference of 6.9°C. Ambient temperatures around the pallet also varied, with an average difference of 0.84°C and a peak of 5.7°C during periods of temperature abuse. This led to the temperature of the product itself rising sharply, with a maximum recorded temperature of 4°C. The study also highlighted the importance of setting appropriate temperature monitoring criteria. While industry experts initially recommended a restrictive temperature range of 0.5°C to 2.0°C, the study suggested that a more liberal threshold of 1°C would result in fewer false alarms and more relevant alerts, thus better safeguarding the quality and extending the shelf life of the transported cod fish. This research underscores the need for careful temperature management in the logistics of perishable goods, influencing best practices in the transport sector to ensure optimal freshness upon delivery.

Aung and Chang (2014) provides significant data on how temperature affects the shelf life of bananas during transportation. Their research established that bananas stored at cooler temperatures (13°C to 16°C) retained 100% of their relative shelf life. However, as the temperature increased, the shelf life decreased, with bananas stored at 16°C to 19°C dropping to 79.68% relative shelf life and those at 19°C to 22°C further decreasing to 62.89%. These findings are crucial for the transportation sector, particularly for those involved in shipping perishable goods like bananas. Proper temperature management can significantly prolong the freshness and quality of bananas, ensuring they reach consumers in the best possible condition.

Thakur and Forås (2015) provides valuable insights into the temperature dynamics within transportation vehicles during the shipment of chilled lamb products. Over a distance of 800 kilometers and a period of 36 hours, the product temperature fluctuated between -0.8°C and 2.7°C. Such variations were influenced by the conditions of food products inside the delivery vehicle. Understanding these temperature fluctuations is crucial for ensuring the quality and safety of chilled lamb upon arrival at its destination. The data suggests that there is a need for robust temperature control and monitoring systems to minimize fluctuations and maintain temperatures within the optimal range for preserving the freshness and quality of chilled lamb products during transit.

Jedermann et al. (2017) examined the transport of bananas and highlighted the significant impact of the container's age on the fruit's preservation during transoceanic shipping. The study noted a variance of about 7.3 days in expected green life, or approximately two weeks, between a 12-year-old container and a 1-year-old container during transoceanic shipping. Besides, the average temperature inside a 12-year-old cooling unit was about 2.5°C higher than that inside a new Thermoking unit. This suggests that the efficiency of the cooling unit diminishes with age, potentially impacting the quality of the bananas during transport. Before the opening of the air flap in the container, CO2 concentrations increased by 0.086% per hour. This was based on a CO2 production rate of 4.5 grams per ton per hour for a given air volume and load. During the ripening phase, CO2 production increased significantly, by tenfold, to 46 grams per ton per hour. These findings highlight the necessity of using well-maintained and up-to-date containers for the transportation of bananas to ensure optimal temperature and CO2 conditions, which are critical for maintaining the fruit's quality and extending its green life during shipping.

The pilot study by Tsang et al. (2018) in Hong Kong showcased the effectiveness of an Internet of Things (IoT)-based route planning system (IRPS) in the transportation of fruits and vegetables, yielding several important advancements: 1) Reduction in Food Spoilage: There was a significant reduction in the rate of food spoilage after the implementation of the IRPS, with a 65% decrease from 22.6% to 7.9% as a percentage of total monthly orders. 2) Decrease in Return Deliveries: The optimized package designs and delivery routes facilitated by the IRPS led to a 63.6% reduction in the number of returns due to cargo discrepancies and food deterioration. 3) Return on Investment: The investment in the IRPS was recouped in just 8.2 months, highlighting the financial viability and benefits of the system. 4) Customer Satisfaction: Complaints dropped by 62.5%, from 8 to 3, and overall customer satisfaction scores improved by 27.7%, from 6.5 to 8.3 points. And 5) Operational Efficiency: On-time performance for order fulfillment improved from 56.8% to 86.1%. These outcomes illustrate how the adoption of an IoT-based route planning system can significantly enhance the efficiency of food delivery services, reduce food waste, and increase customer satisfaction. The study emphasizes the potential of smart technologies in transforming logistics and supply chain management, particularly for perishable goods.

In the study by Jara et al. (2019), IoT sensors were used to monitor the temperature distribution within the transportation environment of perishable goods in Ecuador revealing several key observations: 1) The lowest temperatures were consistently found at the floor, ceiling, and walls of the transport space. 2) There was a steady rise in temperature within the system, reaching 0°C after approximately 40 minutes (2,400 seconds). And 3) The system took about 2 hours (7,200 seconds) to completely stabilize the temperature.

Zhang et al. (2020) utilized a dynamic monitoring and quality assessment system to study the effects of different transportation conditions on the quality of sweet cherries. Three groups were monitored, each under different conditions—average ambient temperature (24.8 °C), ice-added (22.2 °C), and pre-cooled (18.5 °C). Relative humidity averaged 83.6% for the ambient temperature group, 76.15% for the ice-added group, and 74.60% for the pre-cooling group. The implementation of the system led to a reduction in the rate of quality loss by 10%–15% during transit. Additionally, quality changes of sweet cherries can be summarized: 1) there was a decrease in the L* value (brightness) from 29.41 to 28.70, indicating a shift from bright red to deeper red; 2) the cherries' pH increased from 3.58 to 4.40, suggesting a loss of the desired acidic taste; 3) cherry hardness decreased from 5.62 to 4.30, indicating softening; and 4) there was a reduction in SSC from 17.06% to 13.27%, indicating a loss of sugars and flavor compounds. By closely monitoring environmental conditions and adjusting them accordingly, such systems can help maintain fruit quality, potentially leading to better market prices and reduced spoilage.

Wang et al. (2020) investigated the transportation of apples, blueberries, and sweet cherries across China using multi-strategies control, including the application of 1-Methylcyclopropene (1-MCP) and Modified Atmosphere Packaging (MAP), offers significant insights into fruit preservation. Here are the key takeaways:

1. The 1-MCP treatment of apples helped inhibit ethylene synthesis, which is critical for slowing down the ripening process. As a result, the apples retained their firmness and had a lower decrease in soluble solid contents (average reduction of 4.80%), and there was an increase in the ΔE value (indicative of color change) by an average of 8%, all of which are indicative of maintained or improved fruit quality.
2. Temperature impact on ethylene levels of blueberries shows that the group (22 °C) had high ethylene levels above 25 ppm, correlating with the highest spoilage rate of 17.65% and lowest firmness (3.88 kgf) after seven days, compared to other two group at a good temperature-controlled condition.
3. Ethylene concentration and cooling of sweet cherries found that the group (ambient temperature) exhibited the highest spoilage rate of 32.0% and the lowest firmness (4.3 kgf) compared to other two groups (either ice packs in packaging or pre-cooled at 0–1 °C for 12 hours) .

The study emphasizes the importance of controlling ethylene, a gas that accelerates ripening and spoilage in fruits. By using 1-MCP and MAP, along with temperature control strategies, it is possible to significantly extend the shelf life and preserve the quality of perishable fruits. Such practices can reduce food waste and ensure that consumers receive fresher produce. The study suggests that controlling the ethylene levels during transit is crucial and can be effectively managed through these preservation strategies.

Zhu et al. (2022) revealed the transportation of garlic scapes in China over a 700-kilometer journey using a WSN system provides valuable insights into the positive impact of real-time monitoring on food quality and supply chain economics. There was a significant reduction in quality loss of garlic scapes during transit, with initial ranges of 20–30% decreasing to 15%. This indicates that the monitoring and control procedures implemented during transportation were effective in preserving the quality of the garlic scapes. Meanwhile, the market price for fresh garlic scapes in Tianjin more than doubled, reflecting the enhanced quality and value of the product due to effective transportation strategies. These results support the potential for such technology to make supply chains more efficient and profitable, by ensuring that the quality of the product is maintained from the point of origin to the market, thus commanding higher prices and reducing losses.

Jaques et al. (2022) presented numerous noteworthy findings from their study by the use of IoT sensors in the transportation of soybeans in Brazil. The soybeans' intergranular temperature declined slightly during a 240-minute period, going from an initial range of 27.9-28.4°C to 27.5-28.2°C for group I and from an initial range of 28-29°C to 28-27°C for group II. In addition, the relative humidity (RH) of the air changed over the course of the 240-minute period, rising for group II and falling for group I over the course of the same period from 95-98% to 82.5-83.5%. Because of the drop in air temperature, group I's soybeans' equilibrium moisture content (EMC) rose, going from an initial 10.05–10.07% to 10.9–10.1%. On the other hand, throughout the course of the same 240 minutes, group II's EMC dropped from an initial range of 9.86-9.90% to 9.83-9.88%. Furthermore, there were variations in the CO2 content in the surrounding air, with group I experiencing a range of 338-550 ppm. During the 240-minute assessment period, group II had a notable increase in CO2 content from 1000 ppm to 3600 ppm, which may indicate spoiling. Finally, the research found that during the course of the 240 minutes, the estimated dry material loss (LDM) for both varieties of soybeans increased from 0% to 0.032%. Soybeans in groups I and II were found to have germination rates of 79% and 6%, respectively. Also, group I soybeans had a crude protein value of 39.28%, whereas group II soybeans had a crude protein content of 34.79%. These results demonstrate how transportation circumstances affect the safety and quality of soybeans.

The transportation of citrus fruits in South Africa during transit to the Northern Hemisphere through the use of digital twin technology was investigated by Shrivastava et al. (2022). Citrus fruits were found to have signs of severe shriveling after 10 days of storage at room temperature, which made them unsaleable. The mean values for shelf life due to transpiration and respiration were 10.3 and 8.5 days, respectively. This indicates that the fruit's sell-by date is more influenced by its respiration rate rather than water loss through transpiration. Meanwhile, moisture loss ranging from 0.8% to 2.0%, with a mean value of 0.97%, impacts the sellable weight of the fruits, directly affecting the profitability for producers and merchants.

Notable temperature variations were noted in the research by Skawińska and Zalewski (2022), which examined the transportation of perishable items, such as milk, meat, fish, vegetables, fruits, and eggs, in Poland using IoT sensors. The internal temperature of the vehicle rose from 12°C to 18°C during the journey. Additionally, a particular temperature trend that showed a steady rise in temperature from 12°C to 17°C was caused by the repetitive opening and closing of a refrigerated truck. The aforementioned results underscore the need of preserving constant temperature conditions when transporting perishable commodities and shed light on the influence of extraneous variables, like regular truck access, on temperature regulation.

Significant variations in temperature and relative humidity were found in Aguiar et al. (2022)'s study on the use of a wireless sensor system for the transportation of different perishable goods, such as milk, meat, fish, vegetables, fruits, and eggs, in Portugal. These differences might be as much as 7.4°C and 35.3%, respectively. These results highlight the difficulties in preserving constant and ideal environmental conditions when horticultural items are being transported, emphasizing the significance of accurate monitoring and management to guarantee the commodities' quality and safety.

Researchers have paved the way for more effective, affordable, and sustainable transportation procedures by comprehending the effects of variables including temperature variations, ethylene levels, and environmental circumstances. These results highlight the necessity of ongoing observation, evaluation of quality, and use of cutting-edge technology to reduce the hazards related to the transportation of perishable items. Furthermore, the research indicates that there are both financial and environmental advantages to investing in cutting-edge transportation techniques. Among the many benefits of putting these discoveries into practice include less food spoilage, decreased carbon emissions, and increased consumer satisfaction. The significance of temperature management and monitoring, together with the implementation of methods such as 1-MCP and MAP, become apparent in this particular situation.

4.2.4. Storage and Distribution stage

The storage and distribution phases of the contemporary supply chain are crucial in establishing the perishable commodities' quality, safety, and shelf life. Here, protecting the integrity of goods ranging from fruits and vegetables to meats and seafood depends on the difficulties of keeping ideal temperature and humidity levels as well as keeping an eye on other environmental aspects. The usage of IoT and wireless sensor systems, packaging methods, temperature variations, and other variables all play a role in this complicated stage. This study explores 10 different research that provide important insights into the variables that might determine the quality and freshness of perishable commodities. The investigations focus on different elements of storage and distribution.

In the study by Ruiz-Garcia et al. (2008), wireless sensor devices were used to monitor environmental conditions affecting fruit quality during storage and transit. Data was gathered using Xbow and Xbee, two distinct sensor systems. Regarding the Xbow system, the temperature varied from 8.40°C ± 1.1 to 9.06°C ± 0.3, while the reported relative humidity (RH) varied from 62.1% ± 0.7 to 67.6% ± 2.1. On the other hand, the temperature swings recorded by the Xbee system ranged from 3.60°C ± 0.3 to 3.71°C ± 0.4, while the relative humidity measurements varied between 84.1% ± 2.1 and 86.0% ± 3.3. These results show that depending on the type of sensor system, results may vary in temperature and humidity measurements.

Eom et al. (2014) investigated the impact of variable temperature conditions on the use-by date of pork during transportation and storage. The study concluded that at a constant temperature of 22°C, the pork's use-by date was approximately 12.03 hours. Conversely, when maintained at a stable 4°C, the use-by date extended significantly to about 181.28 hours, emphasizing the importance of cooler temperatures in preserving meat quality. These results highlight how variations in temperature during transit and storage can impact the safety and shelf life of animal products.

Musa and Vidyasankar (2017) highlighted the consequences of delayed technological response in the RFID system, notably the absence of fog nodes, on blackberry storage and transportation in Canada. The research revealed that such delays led to a reduction in shelf life for about 30% of the blackberry pallets. The finding underscores the critical role that RFID technology, including fog nodes, plays in preserving the quality and shelf life of perishable products such as blackberries during storage and transportation processes.

Tsang et al. (2018) deployed an IoT-based risk monitoring system (IoTRMS) to evaluate the shelf life and quality of various food products in China, encompassing meat, seafood, vegetables, and fruits under varied storage conditions. Key findings include:

- Fresh meat was stored between -8.3°C to -0.7°C, which correlated with a shelf life of 4.3–7 days.
- The rate of quality deterioration varied across the supply chain segments (Supplier, Processor, Distributor, Retailer), with rates ranging from -14.3 to -23.26.
- Implementation of the IoTRMS led to a 60% reduction in the accident frequency rate, enhancing safety and risk management.
- A 25% increase in idle recovery time was noted, indicating more time for system recuperation and maintenance.
- There was a 14.1% increase in the order fulfillment rate, reflecting more efficient delivery of consumer purchases.
- Workforce stability improved by 13.1%, suggesting enhanced job satisfaction and reduced turnover with the integration of IoT technology.

In the research by Feng et al. (2019), a wireless sensor system was utilized to monitor the shelf life of shellfish under various temperature conditions, revealing significant insights:

- At -9.6°C, during actual cold chain transport, the estimated shelf life of shellfish was 290.05 days. Quality loss was also assessed, with a substantial 48.26% loss noted during transport at -9.6°C.
- Shellfish stored at -17.4°C in a retail setting had a considerably extended estimated shelf life of 546.05 days. Shellfish stored at -17.4°C in a retail environment experienced a minimal quality loss of only 2.59%.
- When refrigerated at -12.4°C, the estimated shelf life was 398.47 days. A 28.92% quality loss was estimated for shellfish stored in a refrigerator at -12.4°C.

Torres-Sánchez et al. (2020) employed a wireless sensor system to observe the impact of temperature on lettuce during storage and transportation in Spain, with key findings as follows:

- The weight loss of lettuce rose with increasing temperature throughout the course of a 29-day storage period; on the last sample day, it reached 4.0% at 20°C, 3.4% at 15°C, 2.4% at 10°C, 2.1% at 5°C, and 2.2% at 2°C.
- Higher temperatures were shown to increase the rate of respiration in lettuce, suggesting a temperature-dependent impact.

- The titratable acidity (TA) of lettuce kept at various temperatures did not significantly vary over time.
- For brief storage periods, soluble solid content (SSC) and pH were rather stable at higher temperatures (20°C, 15°C, and 10°C); however, over longer storage times (21 and 29 days), SSC significantly decreased at 5°C and 2°C. During extended storage at 5°C, the pH rose by 4.0%.
- However, temperature fluctuations had little effect on the stiffness and color (ΔE) of lettuce. The study demonstrated temperature fluctuations during travel in land transportation trials conducted in several European nations.

These results highlight how crucial temperature management is to preserve the quality and freshness of lettuce during storage and transit and beneficial use of wireless sensor systems during storage and transportation in unstable environments for monitoring several parameters to prolong shelf life of vegetables.

Moreover, In the study conducted by Torres-Sanchez et al. (2021) in Spain, wireless sensor systems were employed to monitor the storage and transportation conditions of lettuces. The experiments focused on different setpoint temperatures, namely 10°C, 5°C, and 2°C. Results revealed temperature variations within these setpoints throughout a one-month period. At the setpoint of 10°C, the recorded temperature fluctuated between 10.20°C and 10.62°C. Similarly, at 5°C, the observed temperature ranged from 4.52°C to 5.30°C, while at the lower setpoint of 2°C, temperatures varied between 1.98°C and 3.00°C. These findings provide valuable insights into the temperature dynamics during storage and transportation, emphasizing the importance of precise temperature control to ensure optimal conditions for lettuce preservation. Such data is crucial for enhancing the quality and shelf life of vegetables in the supply chain, ultimately contributing to food safety and minimizing waste.

You et al. (2022) focused on the transport and storage of perishables like onions, potatoes, and apples, applying IoT sensors and simulations to monitor thermal dynamics. Key findings include:

- The biophysical model closely matched the actual thermal behavior of large avocados, with a minimal difference of 3.0% in seven-eighths cooling time (SECT) between the model and real avocado cores.
- Small avocados showed a discrepancy of 5.9% for half-cooling time (HCT) and 0.4% for SECT, indicating the model's effectiveness, especially for larger avocados.
- For large potatoes, the biophysical model's predictions were close to actual cooling times, with variances of 1.4% for HCT and 5.4% for SECT.

However, disparities were noted between small biophysical potatoes and their actual counterparts. The study also emphasized the importance of sensor placement and monitoring, especially for apple storage:

- Acknowledging temperature heterogeneity within cooling chambers, the importance of employing multiple sensors at different stages, such as during harvest and subsequent chilling in fully stocked storages, was highlighted.
- The research underscored the risks of relying on a single sensor through these variable stages of apple preservation.

These insights underline the significance of advanced modeling and sensor deployment in ensuring the integrity and quality of perishables throughout the supply chain.

Yu et al. (2022) studied the use of colorimetric sensors (based on Ag-Fe NTs) for chilled broiler meat, which is packaged with modified environment packaging during storage and transportation. By using this creative packaging technique, the meat's shelf life was increased, and its quality was preserved at various storage temperatures. The study's findings showed that temperature had a major effect on how the color of the meat changed with the use of sensors. After six days of storage at 4°C in packaging with a modified environment, the color changed from bright yellow to light brown. On the other hand, the color shift happened faster at higher temperatures. The color shift happened after 3 days and 12 hours at 10°C and three days at 25°C. The significance of temperature management in maintaining the quality of chilled broiler meat during storage and transportation is underscored by these findings. When paired with proper temperature control, modified environment packaging may be a useful tool for slowing down color changes and extending the shelf life of meat products.

Zhang et al. (2022) studied how to store and ship a variety of fruits, such as plums, blueberries, and strawberries. To keep an eye on the quality and shelf life of these fruits under various packing scenarios, researchers used a wireless sensor system. The results showed that strawberries packaged in Ag-MOFs@CMFP (Ag-Metal-Organic Frameworks incorporated into composite multilayer flexible packaging) remained fresh after 7 days at room temperature, while unpackaged strawberries spoiled within the same timeframe. For both plums and blueberries, a comparable pattern was seen, with packed samples holding their quality longer than unpackaged ones. After 7 days, unpacked fruits (plums, blueberries, and strawberries) lost a large amount of weight, while packaged fruits lost a much less amount of weight. For instance, after seven days, the weight loss of naked strawberries decreased by over 45%, but the weight of packed strawberries was kept at over 70%. Comparable patterns of weight retention were seen for plums and blueberries. Furthermore, the fruits in the control group showed signs of spoiling when their pH levels rose over time. The fruits packaged with Ag-MOFs@CMFP, on the other hand, exhibited much lower rises in pH levels, underscoring the importance of maintaining fruit quality throughout storage and transit. This study demonstrates how well-thought-out packaging options, such as Ag-MOFs@CMFP, may preserve the quality and lengthen the shelf life of perishable fruits while they are being transported and stored.

The stage of storage and distribution involves a complex relationship between innovative packaging, temperature control, and cutting-edge technology. The collection of studies emphasizes how important this step is to maintain the quality and shelf life of perishable items. When it comes to fruits, meats, or veggies, the right temperature and humidity levels may make all the difference in the world. IoT and wireless sensor systems are effective tools for protecting the quality of commodities and keeping these circumstances under control. Self-healing coatings and other smart packaging techniques are showing promise in extending shelf life. But it's not just about keeping everything perfect - it's also about adjusting to the difficulties presented by temperature changes during transportation and the subtleties of packaging materials.

4.2.5. Retail stage

The retail stage acts as a critical nexus in the supply chain, bridging distribution logistics with consumer demand. Effective strategies in this area can significantly impact overall sustainability and profitability through inventory management, waste reduction, and product quality assurance converge. The 5 papers included in this review as follows:

Technology integration: These studies often examine how technologies such as IoT, AI, and smart packaging can enhance product monitoring and inventory management, leading to better quality control and waste minimization. The research by Aytaç and Korçak (2021) demonstrated the impact of IoT technology in reducing food waste within the Quick Service Restaurants (QSRs) industry. By implementing IoT solutions, the two pilot restaurants in Turkey were able to achieve a 10% reduction in food waste over a one-week period. This significant reduction illustrates the potential efficiency gains and sustainability benefits that IoT technology can offer to fast-food outlets, particularly in terms of managing inventory and reducing the environmental footprint associated with food waste.

Dynamic pricing models: Dynamic pricing strategies can be pivotal in managing perishables and reducing waste. By adjusting prices in response to changes in demand, shelf life, and supply levels, retailers can incentivize consumers to purchase products that are approaching the end of their shelf life, thus minimizing waste. This approach requires sophisticated data analysis and real-time responsiveness to market conditions, which can be facilitated by technologies such as IoT and machine learning. For example, a retailer might lower the price of a batch of fruit that is nearing its expiration date to encourage immediate purchase, or conversely, increase prices when demand is high, and supply is limited. The success of such strategies hinges on the ability to accurately predict consumer behavior and adjust pricing in a way that balances the goal of reducing waste with the need to maintain profitability. The study by Vahdani and Sazvar (2022) identifies that the predicted value of product loss in a retail environment for composite foods such as pasta salad is influenced by both the level of social learning among consumers and the initial inventory levels held by the retailer. The range of possible product loss (from 0 to 30 units) indicates that the behavior of consumers is influenced by others in their social network or surrounding environment. When consumers are more attentive to the purchasing decisions of others, they tend to adjust their behavior accordingly. If the social learning (denoted by "k") is high, consumers may be more likely to purchase products they see others buying, potentially reducing waste. Starting with higher inventory levels can lead to increased waste since there is less flexibility in pricing and purchasing decisions. Furthermore, adjusting prices in response to inventory levels and consumer demand can mitigate waste. This requires retailers to be agile and responsive to changes in both market demand and the social learning process. By integrating social learning dynamics into pricing and inventory decisions, retailers can tailor their approaches to minimize waste, ultimately leading to more sustainable practices and potential cost savings.

Inventory optimization: Other studies focus on inventory strategies, exploring how predictive analytics can optimize stock levels, reducing spoilage while meeting consumer needs. The study by Wei et al. (2022) in China on perishable goods in retail environments highlights the complexities of inventory management and the reduction of food waste through dynamic policies. The research investigated the efficacy of various dynamic lateral transshipment policies on profit, cost control, and food waste reduction in retail settings. Specifically, the study compared the No Recycling Policy with Quality Matching Penalty (NRP-QMP) and No Recycling Policy with Lateral Transshipment Penalty (NRP-LFP), revealing no significant difference in food waste between them, indicating that the prohibition of recycling rendered the adjustment of value function approximation techniques moot. Notably, food waste increased with demand uncertainty across all policies except the Partial Food Recycling Policy (PFP), underscoring the relationship between demand unpredictability and waste. The study also suggests that regulatory interventions promoting food recycling through incentives, such as tax breaks, and penalties for waste could encourage retailers to adopt more effective inventory strategies, thereby reducing food loss. Among the policies tested, the Lateral Food Redistribution Policy (LFP) was superior in managing profit and costs, and in minimizing waste, especially under high demand uncertainty and in the presence of rigorous regulations. This research contributes to the ongoing discussion on sustainable retail practices by indicating that dynamic and flexible inventory policies, supported by appropriate regulatory frameworks, can significantly mitigate food waste while ensuring economic benefits for retailers.

Consumer behavior Analysis: Understanding consumer preferences and behaviors is crucial, with research delving into how retail environments can adapt to these patterns to improve sales and reduce waste. However, no specific research has been found in this area.

Sustainability practices: Research also delves into sustainability practices at the retail level, proposing solutions for environmental impact reduction through better supply chain management. A Dynamic Expiration Date (DED) mode was used for 58 specific fresh goods, including a range of fruits, vegetables, meats, and fish, during their retail in a research carried out by Zou et al. (2022) in China. The goal of the DED mode was to maximize expiry dates according to different temperature conditions. The findings showed that, depending on the temperature range, the DED mode had a significant effect on food waste. It significantly decreased food waste by about 10.02% at cooler temperatures (0−8°C). However, the DED mode increased food waste by around 15.94% and 31.71%, respectively, at higher temperatures, notably in the ranges of 12−18°C and 20−28°C. The DED mode significantly reduced food waste under Low Temperature and Medium Quality (LT-MQ) circumstances, by 15.99% for items with a 7-day shelf life. Conversely, for items with longer shelf lives of 120 days and 180 days, respectively, the decreases were around 8.15% and 1.7% under Low Temperature and High Quality (LT-HQ) settings. However, for goods with a 7-day shelf life, the DED mode resulted in a significant increase in food waste by around 57.49% under High Temperature and High Quality (HT-HQ) settings. For items with 120-day and 180-day shelf life, respectively, it increased waste by just 17.87% and 9.86%, respectively. These results highlight how important shelf life and temperature are to the DED mode's ability to reduce food waste in the retail supply chain. The mode worked best for items with longer shelf life and at lower temperatures; it was less successful at higher temps. Moreover, Seo et al. (2016) conducted research in South Korea that examined the application of a biosensor - a wireless sensor system - for the purpose of detecting bacteria in raw fish and shellfish in a retail setting. The purpose of the study was to evaluate how well the conventional procedure for bacterial identification performed in comparison to the biosensor-based approach (EOC sensor). The investigation discovered that the performance of the EOC sensor and the conventional protocol approaches was the same for raw fish samples. They often found samples that had been injected with 100 CFU of the bacteria. As opposed to raw fish, both assay findings for shellfish samples showed a more sensitive performance. Even samples containing as few as 10 CFU of the bacteria were able to yield somewhat beneficial outcomes. The same meal sample (shellfish) was subjected to repeated analyses as part of the investigation. In 80% of the instances, positive results were obtained using the usual methodology, but 40% of the cases showed positive results using the EOC sensor. This shows that the conventional methodology was able to identify bacterial contamination in these samples more successfully. The study found that when 10 CFU of bacteria were introduced into actual samples, the minimum bacterial titer detectable with the EOC sensor was 1.4 × 104 CFU/mL. These results demonstrate the promise of biosensor-based systems for quality assurance and food safety, particularly when it comes to identifying bacterial contamination in marine products.

In sum, these research projects provide a thorough understanding of the retail arena as a vital and ever-changing participant in the battle against food waste. The retail industry's discoveries and innovations will eventually help customers and the environment by fostering a more responsible and efficient supply chain, especially as the need for sustainability and quality assurance develops.

4.2.6. Multiple stages

There are 9 academic articles that elucidate the pivotal role of technology and data-driven solutions in optimizing various facets of the food supply chain, emphasizing their potential to reduce waste, enhance environmental sustainability, and improve overall operational efficacy.

Shih & Wang (2016) analyzed the production and sale of braised pork rice, a composite dish, with a focus on energy efficiency and economic outcomes facilitated by the implementation of a wireless sensor system. The findings show that the central kitchen experienced a significant reduction in electricity usage, which correlated with a substantial increase in revenue per kilowatt-hour, jumping from US$14.23 to US$18.64. Retail operations also saw an uptick in economic efficiency, with turnover per kilowatt-hour rising from US$4.32 to US$4.58. From an environmental perspective, the study noted a 10% reduction in annual energy costs associated with cooling. Beyond energy savings, the study reported broader economic benefits, including the creation of 150 jobs and a substantial boost to the local economy. The investigation also highlighted a remarkable 36% year-over-year increase in braised pork rice sales, from 4.44 million bowls in 2009 to over 6 million bowls in 2010.

Xiao et al. (2017) investigated the impact of various factors on grape quality by employing a wireless sensor system throughout the grapes' post-harvest life cycle, including harvesting, transportation, storage, and distribution in China. The research found that he estimated shelf life based on firmness was 56 days at 0°C, closely aligning with the actual measured shelf life of 58 days. Similarly, when considering the moisture loss rate, the estimated and measured shelf lives were 52 and 56 days at 0°C, respectively. Temperature was found to be a critical factor affecting grape quality, with a recorded maximum temperature fluctuation of approximately 30°C during harvesting and sale and a minimal fluctuation near 0°C during storage and transit. This variation significantly impacted firmness, with a 50% reduction after 53 days at 0°C, whereas a similar decline was observed within just 3 days at 30°C. The study also noted that quality degradation processes, such as firmness loss, accelerated at higher temperatures, requiring only about 3 days at 20°C, 25°C, or 30°C for notable degradation, in contrast to nearly 50 days at 0°C.

Wang et al. (2018) investigated the effects of the supply chain environment on honey peach quality during the Shandong-Singapore export chain using a multi-sensor-managed traceability system. The results show a significant reduction in quality loss, from an initial range of 25-30% to less than 13%. Meanwhile, a substantial loss in meat hardness (61.62%) was observed, alongside a slight decline in SSC (1.41%). The findings suggest that meticulous monitoring and management of these environmental factors can lead to a reduction in quality loss during transportation and storage, thereby preserving the fruit's freshness and extending its marketability. The multi-sensor-managed traceability system provided valuable insights into the supply chain's environmental conditions and their effects on perishable produce.

Also, In the research conducted by Wang et al. (2018) in China, a wireless sensor system was implemented to monitor the entire supply chain of North American holly, encompassing harvesting, storage, transportation, retail, and sale. The market price of holly bundles (ten branches) increased significantly from below 20 yuan/bundle to above

50 yuan/bundle. The study demonstrated that the quality loss of fresh-cut holly branches decreased from 25-30% to below 15% during transportation from Weihai to Beijing, covering approximately 2.5 days and 800.6 km. Temperature variations were observed across different stages of the supply chain, emphasizing the importance of temperature control. Relative humidity and ethylene concentration fluctuated throughout the process, with specific trends in each segment. The respiration rate of the holly followed distinct patterns, reaching maximum values before segment S2 and undergoing fluctuations in subsequent stages. Additionally, moisture content showed a gradual decline from before harvesting to the sale stage. These comprehensive insights into the environmental conditions and quality parameters throughout the supply chain underscore the significance of wireless sensor technology in optimizing the handling and preservation of fruits, contributing to enhanced product quality and economic value.

IoT sensors built into refrigerator cabinets were used in the study of Ramírez-Faz et al. (2020) to keep an eye on the storage and retail conditions of a variety of perishable goods, such as dairy, meat, charcuterie, and frozen foods. The system was installed in a store on 25 January 2018, and it remained active until 15 August 2019, during which time it was thoroughly assessed. Functionality, system performance, and cost-effectiveness were the main evaluation criteria. During operation, the system successfully produced seven alerts, giving early indications for equipment problems to avoid cold chain breakdowns. Adaptability is increased by the ability to configure these characteristics for different types of cabinets. Crucially, these alerts had an immediate effect, where the system's quick action resulted in the withdrawal of a product and prevented losses of €1,500 - It has been indicated that the value of stored products are $2200-1480, $2800 and $1500 for dairy, meat/charcuterie and frozen foods, respectively.- The decentralized alarm notification system ensures prompt action to prevent potential financial losses by enabling each device to independently handle alarms connected to the monitored equipment. Moreover, during the day, the temperature variations were noted to occur within particular ranges. The temperature fluctuated between 2 and 15 °C for charcuterie goods and between 6 and 15 °C for dairy products. It's crucial to remember that the refrigerated cabinets' fixed point temperature was 2°C. This emphasizes how critical IoT sensor technology is for protecting product quality and ensuring proper storage conditions while avoiding financial losses.

Urbano et al. (2020) aimed to assess the effectiveness of RFID technology in tracking the temperature conditions during the transportation and retail stages of perishable goods, specifically oranges and pumpkins. The experiment findings indicated certain temperature ranges and exposure times for these products. For the pumpkin experiment, pumpkins were kept at a temperature of 3.2–5.2°C for around 14.96 days during the transit and retail stages. However, during transportation, there was a slight increase in temperature, ranging from 5.8–8.4°C, lasting for about 6.86 days. Additionally, the manipulation time, where the temperature varied from 9–22°C, was recorded for approximately 3.99 hours. For the orange experiment, It took 8.8 days to get oranges from Valencia, Spain, to Cork, Ireland. The oranges were kept at an appropriate temperature for the first 3.68 days. Nevertheless, temperatures between 9 to 22°C were exposed during the next 4.25 days, exceeding the ideal range for oranges. It's important to note that no cold chain break was found throughout this transit because the oranges did not reach the lower breakpoint of below −5°C and the lowest temperature recorded was 1°C. These results underline how crucial it is to keep an eye on the temperature during the shipping and retail stages in order to retain the perishable goods' quality and safety and beneficial use of RFID tags in this regard.

In the study conducted by Stramarkou et al. (2022) in Greece, a Life Cycle Assessment (LCA) was carried out to evaluate the environmental impact and production cost of Smart Packaging (SP) involving CO2 sensor in comparison to Conventional Packaging (CP). The findings of the study regarding these packaging types are as follows.

- Carbon Footprint: At the production stage, the carbon footprint of CP (Conventional Packaging) was determined to be 1.52 × 10^-1 kg CO2eq., while SP (Smart Packaging) exhibited a higher footprint, approximately 2.44 × 10^-1 kg CO2eq., which is 59.7% higher. This indicates that the production of SP is associated with a greater initial carbon footprint.
- Environmental Performance Post-Production: Consideration of stages following packaging production altered the trend in environmental performance. In these post-production stages, the carbon footprint of CP increased to 4.97 kg CO2eq. However, SP showed a modified environmental performance in various scenarios. In the optimistic scenario, the footprint of SP was lowered to 3.93 kg CO2eq., in the realistic scenario it was 4.16 kg CO2eq., and in the conservative scenario it was 4.61 kg CO2eq. The study assessed the performance across multiple impact categories, including positive, almost equivalent, and negative outcomes.
- Impact Categories: Under the conservative scenario, SP demonstrated improved environmental performance in 7 impact categories, with negative rates indicating reductions in environmental impact. In 6 categories, SP performed almost the same as CP, with rates ranging from 0 to 1%. However, in 5 categories, SP exhibited worse performance, with rates ranging from 4.7% to 13.0%. These impact categories encompass aspects such as fossil depletion, ionizing radiation, and various aspects of photochemical ozone formation, including effects on ecosystems and human health, as well as terrestrial ecotoxicity.
- Production Cost: The study also assessed the production cost of SP, which was determined to be 0.23 EUR. This cost was found to be 84.4% higher than the production cost of CP.

These findings highlight the trade-offs between Smart Packaging and Conventional Packaging in terms of environmental performance, carbon footprint, and production cost, providing valuable insights for decision-makers in the packaging industry and beyond. The choice between these packaging options may depend on specific environmental goals and economic considerations.

In the comprehensive research conducted by Luo et al. (2022), a wide array of food categories, including cereals, pulses, seeds, nuts, roots, tubers, plantains, fruits, vegetables, and meat, was analyzed across multiple stages of the global food supply chain. The study employed various Internet of Things (IoT) applications, such as temperature and humidity sensors, utilizing mathematical modeling and Life Cycle Assessment (LCA) to gauge their impact. The findings showcased a remarkable reduction in the consumption of shelf lives (SLs), ranging from 31.2% to 40.2%, depending on the specific food category. This decrease translated into substantial extensions of Effective Shelf Lives (ESLs), ranging from 57 to 116 hours for fruits, vegetables, and meats. Furthermore, the research uncovered a significant reduction in food loss (FL) by weight, ranging from 20% to 41%, with the highest impact observed in perishable bananas and apples. Notably, the study highlighted the critical role of sensors in environmental sustainability, with only 14% of sensors engaged in monitoring meat and animal products contributing to an impressive 84% global carbon emission reduction. This nuanced analysis underscores the differential impacts of IoT sensor applications across diverse food categories, emphasizing their potential for targeted and effective environmental mitigation in the complex landscape of the global food supply chain.

In the research conducted by Zhu et al. (2022), IoT sensors were applied to various food categories, including fruits, vegetables, roots, tubers, plantains, meat, cereals, pulses, seeds, nuts, and more. The study covered multiple stages of the food supply chain, from planting and harvesting to processing and marketing, with a focus on both perishable and non-perishable foods. The research had a global scope and employed mathematical shelf-life (SL) modeling and Life Cycle Assessment (LCA) to assess the impact of IoT sensor applications. The study revealed the following significant findings:

- Shelf-Life Extension (SL): Improved food supply logistics enabled by IoT sensors resulted in a substantial increase in the shelf life of various food categories. The SL was extended by 33.6 ± 6.4% for bananas, plantains, and apples, 40.2 ± 31.5% for other fruits and vegetables, and 31.2 ± 18.7% for meat and animal products. This led to prolonged SLs ranging from 71 to 116 hours for bananas, plantains, and apples, 57 to 94 hours for other fruits and vegetables, and 65 to 85 hours for meat and animal products.
- Food Loss (FL) Reduction: IoT sensor applications had a significant impact on reducing food loss (FL) by weight. 1) For the first three perishable food categories, FL was lowered by 25 to 41%. IoT interventions had a notable impact on reducing FL by weight. For perishable bananas and apples, FL was reduced by 25-41%. For perishable fruits and vegetables, FL decreased by 20-33%, and for perishable meat, it was lowered by 20-26%. Additionally, there was a 5% reduction in FL for non-perishable cereals, pulses, and starchy roots. And 2) Furthermore, during the storage and transport stages, FL was reduced from an initial 50-58% to 5-7%. At the processing and wholesale stage, FL was diminished by 27-33%. Collectively, IoT sensors contributed to a global reduction in FLs by 9.7 million tons.
- Environmental Impact: The study assessed the environmental burden of different

food categories in the upstream of the food supply chain. Meat and animal products were found to have the highest environmental impact per kilogram, which could be up to 78 times higher than that of bananas, plantains, and apples. Non-perishable foods exhibited the least environmental impact except in the case of one index, where the impact was 179 times lower than non-perishable food in the upstream of the food supply chain.

- Sensor Leverage Effect: The application of IoT sensors had a notable leverage effect on seven environmental aspects out of ten indexes studied. The study provided emissions data for various sensor models. 1) The study also examined the deployment of IoT sensors in the food supply chain. Only 14% of the sensors were used to monitor meat and animal products, but these sensors contributed the most to carbon emission reduction, achieving an 84% global reduction. In contrast, the larger number of sensors (65%) used for fruits and vegetables led to a disproportionately lower level of carbon mitigation, equivalent to 6.7% of global carbon emission reductions; and 2)The average emissions per kilogram of food varied by food category and sensor type. For fruits and vegetables, sensor models had emissions of 1.3, 0.2, and -0.5 kgCO2eq for manufacture, electricity, and operation, treatment, and recovery, respectively. For bananas, plantains, and apples, the values were 1.35, 0.2, and -0.5 kgCO2eq, and for meat and animal products, they were 1.35, 0.2, and -0.45 kgCO2eq. Non-perishable cereals, pulses, and starchy roots had lower emissions, with values of 0.35, 0.05, and -0.1 kgCO2eq.

These findings underscore the positive impact of IoT sensor applications on extending shelf life, reducing food loss, and influencing the environmental footprint of various food categories, highlighting the variation in impacts across different stages of the food supply chain.

The papers included in this group highlight how important technology and data-driven solutions are to streamlining the food supply chain at all levels. A number of areas of the food supply chain have significantly improved as a result of the use of wireless sensor systems, IoT technologies, RFID tags, and smart packaging, from production to sale.

4.2.7. Household stages

Several research works have examined the traditional points in the food supply chain; nevertheless, one key article in this collection has delved into hitherto uncharted territories, which is storage at home illuminating the critical function of technology and data-driven solutions. Mezzina et al. (2022) focused their study on food storage (at home) in Italy, utilizing smart home technologies to improve food preservation. Their research demonstrated the serious consequences of inadequate food storage conditions, as even three hours of inadequate preservation might significantly shorten a food item's expiration date by 4.72 days. Interestingly, the research presented a suggested smart home system that, when used in the best possible storage circumstances, only added 0.08 days -roughly one hour- to the food's expiry date. But when food was kept in unfavorable circumstances, this technique proved to be an effective remedy, extending its shelf life by an average of almost 55%. These findings highlight how revolutionary smart home technology may be in reducing food waste, improving food safety regulations, and supporting sustainability goals.

4.3. Recent progress in food sensing area

This review performed network visualization using keyword co-occurrence analysis in VOSviewer to understand the role of IoT solutions in extending shelf life and reducing FLW along the supply chain (Figure 9). Analyzing the co-occurrence of keywords in terms of their frequency and relevance provides an intuitive means to discern research trends and identify cutting-edge topics. The study searched full documents (articles and early access) of papers in WoS published from 2003 to 2022 with the keywords "shelf life"OR"food waste*" OR "food loss*" AND "smart packaging"OR“sensor” AND "dynamic" OR “real-time” OR "internet of things" OR "IoT". We then create a term co-occurrence map based on text data and use full counting in this review, showing 69 items (7 clusters) and 960 links. The minimum number of occurrences of a term is set to be 5. Based on the scope of the threshold, the number of most relevant terms is to be selected 84. As summarized in Table 1, it is evident that Cluster 1 boasts the highest number of keywords, signifying a centralization of identical themes related to IoT solutions for addressing FLW. The main keywords ranked by occurrence or frequency are “supply chain”, “iot”, “food waste”, “freshness”, “fruit”, “degrees c (temperature)”, “packaging”, “thing”, “detection”, “real time” (Table 2: the top effective keywords). Meanwhile, keywords like “iot”, “algorithm”, “sensor”, “smart packaging”, “wireless sensors network”, “radio frequency identification”, “block chain”, “traceability”, continue to underscore the research hotspots within the technologic domain. On the other hand, the review observed more specific keywords, such as “fruit”, “meat”, “production”, “cold storage”, “cold chain”, “online retailer”, “consumer”, “label”, suggesting the emergence of more actual case studies. Most importantly, this review noticed a shift in keywords post-2020 toward increased environmental and social concerns, such as “environmental impact”, “life cycle assesment”, “co2”, “shelf life extention”, “reduction”, “quality loss”, “marketability”, “critical quality parameter”.

Table 1. Clusters and numbers of keywords.

Cluster	Term	Selected keywords
1	15	accuracy; algorithm; cold storage; color; detection; e nose; freshness; humidity sensor; label; meat; real time; smart packaging; spoilage; temperature sensor; test
2	14	coating; environmental impact; food loss; food packaging; food spoilage; food waste; life cycle assessment; microbial

		growth; nano packaging; production; reduction; shelf life extension; use
3	11	architecture; China; co2; decision; honey peach export chain; quality control; relative humidity; traceability system; transparency; wireless sensors network; wsn
4	10	consumer; mathematical model; online retailer; perishable product; quality assurance; radio frequency identification; retailer; rfid; social learning; user
5	9	advantage; cold chain; implementation; internet; iot; major challenge; product challenge; product quality; thing; wireless sensor network
6	5	criterium; fruit; marketability; quality loss; supply chain
7	5	block chain; critical quality parameter; degrees c; experiment; traceability

Table 2. The top 30 effective keywords by occurrences.

Ranking	Keyword	Occurrence	Ranking	Keyword	Occurrence
1	supply chain	44	16	decision	14
2	iot	40	17	spoilage	14
3	food waste	36	18	consumer	14
4	freshness	30	19	food loss	13
5	fruit	29	20	label	13
6	degrees c	25	21	meat	12
7	packaging	24	22	experiment	12
8	thing	24	23	relative humidity	12
9	detection	24	24	environmental impact	12
10	real time	23	25	traceability	12

11	wsn	22	26	algorithm	11
12	production	20	27	retailer	11
13	reduction	19	28	architecture	11
14	cold chain	18	39	wireless sensor network	11
15	rfid	15	30	quality control	11

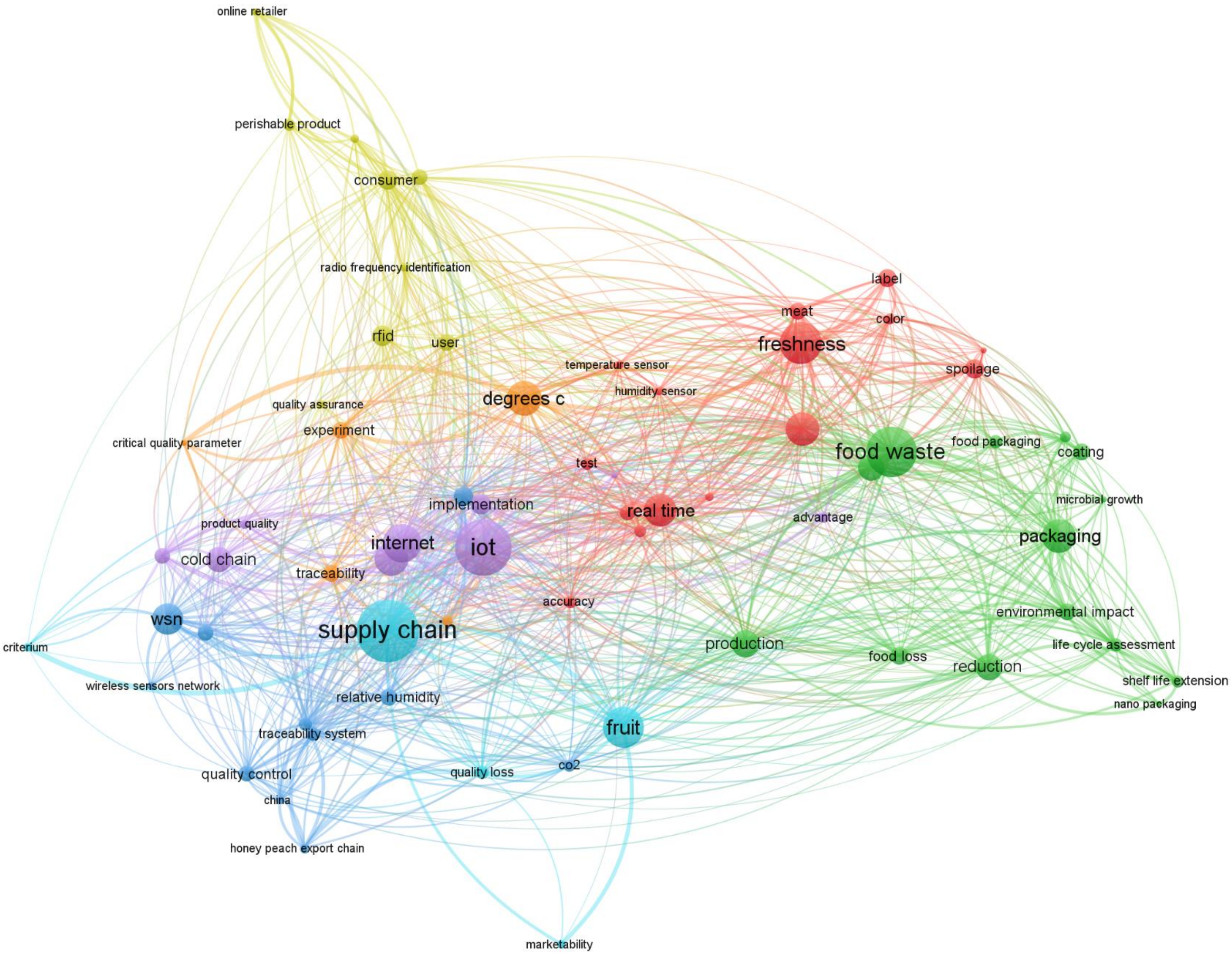

Figure 9. Co-occurrence of keywords (nodes) based on their class using VOSviewer V.1.6.19

5. Discussion

5.1. Comparative analyses across studies

5.1.1. Production and manufacturing stage

Through four articles that examine the production/manufacturing stage of the food supply chain, wireless sensor systems show themselves to be effective tools in a variety of food categories. Italy is a leader in this field of study, but the scant literature indicates that this is an uncharted territory.

- Environmental monitoring:

  Common features: Baire et al. (2019) and Zheng et al. (2021) both emphasize the importance of environmental conditions in the production of bread and water. Temperature, humidity and gas concentration are controlled to optimize the process and improve product quality.

  Difference: Siddiqui et al. (2021) does not specifically address environmental monitoring, but focuses on sustainable rice cultivation practices.

- Microbiological stability:

  Common features: Catania et al. (2020) and Zheng et al. (2021) investigated the microbial aspects, emphasizing the microbiological stability of aromatic herbs and variations in the microbial composition of water samples and both present the importance of wireless sensors for the assessment and maintenance of microbiological stability in various food processing contexts.

  Difference: Baire et al. (2019) does not specifically address microbiological stability but focuses on environmental factors of bread making.

- Sustainable practices:

  Common features: Siddiqui et al. (2021) and Zheng et al. (2021) both address sustainable practices and present innovative approaches to rice cultivation to improve water and energy efficiency.

  Difference: Catania et al. (2020) and Baire et al. (2019) do not specifically address sustainable practices, but instead focus on microbial stability and environmental factors.

- Geographic focus:

  Common features: Two studies (Baire et al., 2019; Catania et al., 2020) belong to Italy, indicating that research in the manufacturing and production phases is concentrated in this country.

Difference: Siddiqui et al. (2021) examine sustainable rice cultivation in Bangladesh, providing a geographically diverse perspective.

- Translation and reporting of data:

  Common features: Studies such as Baire et al. (2019) and Catania et al. (2020) there is often a lack of translation of results into numerical results in terms of food waste and environmental perspectives, indicating variability in reporting.

  Difference: Siddiqui et al. (2021) do not specifically address food loss but emphasize water and energy efficiency in rice production.

The comparative analysis highlights commonalities and differences in environmental monitoring, microbiological stability, sustainable practices, geographic focus and data reporting. While the commonalities point to common research topics, the differences point to the need for a more comprehensive and standardized approach to fully exploit the advantages of wireless sensor systems in food production. Further research is needed for comprehensive understanding and global application.

5.1.2. Storage stage

The current debate on food storage and preservation is intricately woven into the threads of technological innovation, with a particular focus on the transformative impact of digital technologies on inventory management. A careful review of 28 studies covering a wide range of food categories, including grains, fruits, vegetables, meats and seafood, reveals a wealth of methods and results. This advanced comparative analysis aims to distill the patterns and variations of these studies, providing a nuanced understanding of the various challenges and innovative solutions in food preservation.

- IoT technology and environmental accuracy:

  Common features: Research consistently highlights the central role of Internet of Things (IoT) technologies such as RFID and Wireless Sensor Networks (WSN) in fine-tuning warehouse environmental monitoring. Badia-Melis et al. (2015), Y. Tsang et al. (2017) and Tervonen (2018) exemplify this trend and present the adaptability of IoT to different storage contexts.

  Differences: While the core theme revolves around environmental monitoring, the specifics of applications range from lemons to seed potatoes, reflecting technology and versatility.

- Quality and freshness control:

  Common features: Studies consistently emphasize the importance of real-time monitoring in evaluating product quality and freshness. Technologies such as electronic noses (E-nose) and smart packaging are emerging as key tools to detect defect indicators. Feng et al. (2020), Yang et al. (2022) and Leite et al. (2022) make significant contributions to this topic.

Differences: Indicators of spoilage vary, including gas concentrations, pH levels and color changes, reflecting the contextual nuances of different food categories and storage methods.

- Integrity of seafood and meat:

  Common features: Seafood and meat preservation studies consistently emphasize the critical role of technology in discerning quality differences, detecting spoilage, and ensuring microbiological safety. Jilani et al. (2019), Banga et al. (2019) and Kilic et al. (2022) make significant contributions to this topic.

  Differences: Different approaches, such as microwave sensing, gas sensors and smartphone apps, highlight the variety of methods used to solve the unique challenges of seafood and meat preservation.

- Informed decision making:

  Common features: Integrating data analysis and machine learning into decision making, as Sharif et al. (2021) and Nair et al. (2021), represents a general trend. Advanced techniques are used to interpret complex data sets and improve decision-making processes.

  Differences: Some parameters and algorithms of data analysis differ, reflecting the applicability of these approaches to different recording contexts and purposes.

- Advantages and Traceability of Blockchain:

  Common features: Studies involving blockchain technology such as Tsang et al. (2019) and Feng et al. (2020) highlight opportunities to improve traceability, transparency and data integrity. Blockchain is emerging as a transformative tool that ensures accountability and reliability of storage processes.

  Differences: The focus varies from degradation rates to monitoring environmental parameters, showing the versatility of blockchain applications in food preservation.

- Synergy of sustainable practices and technology:

  Common features: Studies highlight the role of technology in promoting sustainable practices, whether in rice cultivation or optimizing temperature control for seafood storage (Siddiqui et al., 2021; Giarratana et al., 2022).

Differences: The specific aspects of sustainability discussed, such as water conservation or energy-efficient storage, reflect different challenges in the broader topic of sustainability.

Synthesizing these various studies, a comprehensive narrative highlights the changing impact of technology on food storage and preservation. Real-time monitoring, data-driven decision-making and aspects of sustainability emerge as recurring themes that describe the evolving landscape of the food chain. However, the contextual differences between studies indicate the need for tailored solutions, recognizing the complex interaction between technological interventions and the unique requirements of different food groups. This academic synthesis provides a nuanced understanding of the challenges and opportunities of modern food preservation, paving the way to informed strategies that improve food safety, minimize waste, and optimize storage practices.

5.1.3. Transportation stage

A synthesis of 14 research papers focusing on the transportation phase of the food chain provides a nuanced understanding of Internet of Things (IoT) applications. The purpose of this comparative analysis is to identify commonalities and differences between various perishable products and to identify trends and differences in the adoption of IoT technologies.

- Temperature Management Strategies:

  Common features: Various studies have clearly recognized the central role of temperature control in the preservation of perishable goods during transportation. Wang et al. (2010), Hafliðason et al. (2012) and Aung and Chang (2014) jointly emphasize the importance of maintaining a stable temperature to improve the shelf life and overall product quality.

  Differences: Although the common goal is to optimize the temperature conditions, different methods are used in the studies. Wang et al. (2010) focus on mathematical modeling and strategic planning, Hafliðason et al. (2012) delve into the specifics of seafood transportation, and Aung and Chang (2014) limit themselves to the effect of temperature on the shelf life of bananas. Different contexts require nuanced methods of temperature regulation.

- Conditions for containers and vehicles:

  Common features: Common recognition stems from the importance of container and vehicle conditions in maintaining the freshness of perishable goods. Both Jedermann et al. (2017) and Tsang et al. (2018) emphasize the need for well-maintained containers and efficient route planning systems to minimize contamination during transport.

  Differences: The difference is due to the special conditions of the containers.

Jedermann et al. (2017) highlight the effect of container age on banana shelf life, while Tsang et al. (2018) focuses on the implementation of an IoT-based route planning system. Different aspects of container and vehicle conditions are considered according to the unique challenges presented by different perishable goods.

- Quality maintenance and safety measures:

  Common features: Maintaining the quality of perishable goods during transportation is a common goal. Zhang et al. (2020), Wang et al. (2020) and Zhu et al. (2022) all implement monitoring systems or control strategies to minimize quality degradation during transport.

  Differences: The differences lie in the specific strategies used. Zhang et al. (2020) and Wang et al. (2020) focus on dynamic tracking and multi-strategy control, while Zhu et al. (2022) specifically use a WSN (Wide Sensor Network) system for real-time monitoring of garlic. Different types of perishable products require tailored strategies to maintain quality.

- Environmental factors and digital twin technology:

  Common features: Shrivastava et al. (2022) and Skawińska and Zalewski (2022) investigated the effect of environmental factors Shrivastava et al. the use of digital twin technology in the transport of citrus fruits and the IoT sensors of Skawińska and Zalewski to reveal temperature changes during the transport of various perishable goods.

  Differences: Divergent methodologies are evident, as Shrivastava et al. (2022) focus on the respiration rate's impact on shelf life using digital twin technology, while Skawińska and Zalewski (2022) utilize IoT sensors to reveal temperature variations in Poland, emphasizing the impact of extraneous variables.

- General effects and progress:

  Common features: Jagtap et al. (2021) and Aguiar et al. (2022) both contribute to the discussion of IoT applications in food transport. Jagtap et al. (2021) classify IoT applications into demand and supply components, while Aguiar et al. (2022) deploy wireless sensor systems in Portugal, highlighting significant variations in temperature and relative humidity during transport.

  Differences: The difference is due to specific areas of focus. Jagtap et al. (2021) broadly classify IoT applications with a focus on efficient goods flows, while Aguiar et al. (2022) specifically address the challenges of maintaining environmental conditions continuously during transport.

In conclusion, while the commonalities emphasize the common recognition of key factors, the differences indicate the need for tailored approaches based on the specific challenges of different types of perishable goods and transport. This nuanced understanding contributes to the ongoing discourse on the strategic deployment of IoT technologies in food transportation.

5.1.4. Storage and Distribution stage

The storage and distribution stages of the modern supply chain are central to maintaining the quality, safety and preservation of perishable goods. This comparative analysis examines 10 separate studies, each providing valuable insight into the various factors that influence the storage and distribution of products from fruit and vegetables to meat and seafood.

- Sensor systems for monitoring storage and transport

  Common features: Ruiz-Garcia et al. (2008) and Feng et al. (2019) emphasize the invaluable role of wireless sensor systems in monitoring environmental conditions during storage and transportation. Reliance on accurate data from these systems is critical to ensuring the integrity of perishable goods.

  Differences: However, there are significant differences in technology options. Ruiz-Garcia et al. (2008) used the Xbow and Xbee sensor systems which showed anomalies in temperature and humidity measurement. In contrast, Feng et al. (2019) focused on a wireless sensor system adapted for conservation life monitoring of shellfish, demonstrating a versatile approach to sensor technology selection.

- Effect of temperature on shelf life

  Common features: Eom et al. (2014), Feng et al. (2019) and Torres-Sánchez et al. (2020) jointly emphasize the paramount importance of temperature stability for the shelf life of perishable goods. The common feature is the recognition that temperature fluctuations during transport and storage can significantly affect the safety and preservation of goods.

  Differences: However, studies show commodity-specific effects. Eom et al. (2014) focus on pork, Feng et al. (2019) crustaceans and Torres-Sánchez et al. (2020) in a salad, showing how different temperatures affect different goods. This highlights the need for tailored temperature control strategies based on the nature of perishable goods.

- The role of IoT in risk management and efficiency

  Common features: Tsang et al. (2018) and You et al. (2022) emphasize the broader implications of IoT technology for improving supply chain efficiency and security. Both studies highlight the transformative impact of IoT on risk management, order fulfillment and workforce stability.

Differences: However, the focus of the app is different. Tsang et al. (2018) focus on reducing accident rates and improving order compliance, while Yu et al. (2022) explores the use of IoT to monitor the thermodynamics of onions, potatoes and apples. This difference shows the versatility of IoT applications to deal with different challenges in the storage and distribution.

- Technical delays and RFID effects

  Common features: Musa and Vidyasankar (2017) and You et al. (2022) emphasize the key role of RFID technology in maintaining the quality and shelf life of perishable products. Both studies emphasize the criticality of technical choices to ensure the effectiveness of control systems.

  Differences: However, there is a difference in focus. In particular, Musa and Vidyasankar (2017) examine the consequences of late technological response in RFID systems and highlight the potential risks associated with technological delays. In contrast, You et al. (2022) provides an overview of sensor-based monitoring and reveals the different dimensions of technical aspects in the supply chain of perishable products.

- Packaging innovations to extend shelf life

  Common features: Yu et al. (2022) and Zhang et al. (2022) present the importance of innovative packaging techniques to extend the shelf life of perishable goods. Both studies demonstrate the potential of creative packaging methods to maintain product quality and freshness.

  Differences: However, the differences in material and use are notable. Yu et al. (2022) focus on colorimetric sensors for chilled chicken meat, while Zhang et al. (2022) investigate the impact of wireless sensor systems on different fruits in different packaging scenarios. These different approaches emphasize the importance of adapting packaging solutions to the specific requirements of different perishable goods.

- Temperature control of vegetables

  Common features: Torres-Sanchez et al. (2020) and Torres-Sanchez et al. (2021) jointly demonstrate the crucial role of temperature control in maintaining the quality and freshness of lettuce during storage and transport. Both studies provide a comprehensive picture of the multifaceted effect of temperature on the parameters affecting the storage of vegetables.

  Differences: But the focus on specific parameters is different. Torres-Sánchez et al. (2020) investigated weight loss, respiratory rate, acidity and other parameters, while Torres-Sanchez et al. (2021) focuses on the temperature dynamics of lettuce during storage and transport. This nuanced approach reveals a complex relationship between temperature regulation and storage quality parameters of certain vegetables.

A collective analysis of studies on the storage and distribution of perishable goods provides important insights into key aspects of maintaining quality, safety and shelf life. Technological dependence emerges as a central theme, and the central role of sensor systems and RFID technology is constantly emphasized. Together, the studies highlight the criticality of technology choices in effectively tracking and maintaining the integrity of perishable goods throughout the supply chain. Temperature management stands out as a common thread, revealing different effects on different commodities and highlighting the need for tailored temperature management strategies based on the unique characteristics of each product. In addition, the extensive role of IoT technology can be seen in its impact on risk management, order fulfillment and workforce stability, which contributes to the overall efficiency of the supply chain. Innovative packaging techniques explored in studies of colorimetric sensors and wireless sensor systems demonstrate their effectiveness in extending the shelf life of perishable products. Insights from studies on vegetables, especially lettuce, provide a nuanced understanding of the complex relationship between temperature, weight loss, respiration rate and other parameters, and provide comprehensive guidelines for vegetable storage. Together, these studies contribute to the development of strategies to improve the overall quality and safety of storage and distribution of perishable goods in modern supply chains. In summary, the comparative analysis provides a detailed knowledge of the factors impacting the distribution and storage of perishable commodities by highlighting both similarities and differences among the studies. These revelations aid in the formulation of plans aimed at improving the supply chain's general overall quality and safety.

5.1.5. Retail Stage

Five research articles on the retail stage of the supply chain are examined. The analysis highlights themes and differences among the topics, providing insights into practical approaches to improve sustainability, profitability, and waste reduction.

- Technological integration:

  Common features: Several studies agree on the transformative role of technology, especially the Internet of Things, artificial intelligence and smart packaging, in improving product tracking and inventory management. Aytaç and Korçak (2021) and Zou et al. (2022) both show a positive impact of technology, and Aytaç and Korçak show a 10% reduction in food waste due to IoT adoption.

  Differences: Although there is consensus on the potential benefits, the specific techniques used, and their effectiveness may vary. For example, Zou et al. (2022) focus on the DED mode, while Aytaç and Korçak (2021) emphasize IoT without specifically mentioning DED.

- Dynamic pricing models:

  Common features: Vahdani and Sazvar (2022) and Wei et al. (2022) both recognize the importance of dynamic pricing in managing perishable products and reducing waste by responding to real-time market conditions. Both studies emphasize the need for improved data analysis, and Vahdani and Sazvar emphasize the impact of social learning on pricing decisions.

  Differences: The studies differ in their areas of focus, Vahdani and Sazvar (2022) examine the dynamics of social learning in price decisions, Wei et al. (2022) delve into lateral transhipment practices and their impact on waste reduction.

- Optimizing ad distribution:

  Common features: Wei et al. (2022) and Vahdani and Sazvar (2022) help to understand storage strategies and emphasize the need for dynamic policies to reduce food waste. Both studies acknowledge the impact of regulatory measures such as incentives and penalties in encouraging retailers to adopt efficient inventory management strategies.

  Differences: Studies differ in their specific purpose, Wei et al. (2022) compare lateral transfer policies, and Vahdani and Sazvar (2022) examine the dynamics of social learning. The effectiveness of these policies varies under different circumstances.

- Analysis of consumer behavior: In particular, there is a gap in research related to consumer behavior analysis. Understanding consumer preferences and behavior is considered crucial, but no specific studies on this aspect were found in the reviewed literature.
- Sustainable development practices:

  Common features: Zou et al. (2022) and Seo et al. (2016) both provide an overview of sustainability practices, focusing on the influence of temperature, shelf life and technology in reducing food waste. Both studies highlight the importance of tailored approaches based on product characteristics such as temperature and storage conditions.

  Differences: At different temperatures and storage conditions, Zou et al. (2022), which highlights the complexity of implementing sustainable practices. Seo et al. (2016) focus on biosensor-based quality assurance systems and present the potential and challenges for bacterial contamination detection.

The combined results highlight how complex waste reduction is at the retail level. Although technological integration appears to be a prevalent theme, contextual circumstances influence the efficacy of tactics like inventory optimization and dynamic pricing. The lack of specialized study on consumer behavior analysis points to a possible direction for further investigation. The impact of sustainability policies varies, which emphasizes how crucial it is to take temperature and shelf-life conditions into account. As a result, these studies add to a thorough knowledge of waste reduction tactics used in the retail industry, highlighting the necessity of flexible, technologically advanced methods catered to particular situations.

5.1.6. Multiple Stages

Together, the nine scholarly pieces offer a deep understanding of how technology and data-driven solutions are revolutionizing the different aspects of the food supply chain. These studies cover a wide range of supply chain domains, offering a rich tapestry of innovations, from RFID technology and smart packaging to wireless sensor systems and Internet of Things applications. We explore the similarities and differences between this research in this comparative study, grouping them into discrete themes to provide a thorough overview.

- Energy efficiency and financial results:

  Common features: Shih and Wang (2016) and Wang et al. (2018) both highlight the financial benefits of deploying wireless sensor systems and show increased food and market prices. Both studies emphasize reducing energy use, which promotes economic efficiency.

  Differences: Shih and Wang (2016) focus on braised pork rice production, while Wang et al. (2018) investigated the supply chain of North American holly, showing the versatility of sensor systems in different food contexts.

- Quality control and shelf-life extension:

  Common features: Xiao et al. (2017) and Urbano et al. (2020) both use wireless sensors to monitor and improve the quality of perishable goods, especially grapes and various food categories. Both studies recognize the critical role of temperature in product quality and shelf life.

  Differences: Xiao et al. (2017) focuses on grapes and provides an overview of temperature changes at different stages, while Urbano et al. (2020) cover a wider range of food categories with an emphasis on reducing consumption of preserved life and food waste.

- Traceability and quality maintenance:

  Common features: Wang et al. (2018) and Stramarkou et al. (2022) emphasizes traceability using wireless sensor technology to monitor environmental conditions and maintain product quality. Both studies emphasize the importance of temperature control and real-time monitoring.

Differences: Wang et al. (2018) focus on honey peach and North American holly, while Stramarkou et al. (2022) conduct a life cycle assessment (LCA) to evaluate smart packaging (SP) with CO2 sensors and provide a broader environmental perspective.

- Cold chain management and economic impact:

  Common features: Ramírez-Faz et al. (2020) and Zhu et al. (2022) both use IoT sensors to monitor perishable goods and emphasize the importance of temperature control to prevent economic losses and maintain product quality. Both studies highlight the adaptability and effectiveness of sensor systems in different cold chain scenarios.

  Differences: Ramírez-Faz et al. (2020) focus on the economic impact of sensor alerts preventing the loss of certain products, while Zhu et al. (2022) conduct a global analysis that presents the impact of IoT sensors on extending shelf life and reducing food waste in different food categories.

- Environmental impacts and packaging solutions:

  Common features: Stramarkou et al. (2022) and Zhu et al. (2022) elaborate on the environmental impact of sensor technologies and provide an overview of the carbon footprint and production costs of Smart Packaging and IoT sensor applications. Both studies recognize trade-offs between different packaging and sensor choices.

  Differences: Stramarkou et al. (2022) specifically compares Smart Packaging (SP) and Conventional Packaging (CP), focusing on carbon footprint and production cost, while Zhu et al. (2022) provides a comprehensive analysis of IoT sensors and impact on shelf-life extension, food loss reduction, and environmental aspects across various food categories.

- Global Impact and Internet of Things (IoT) Applications:

  Common features: Luo et al. (2022) and Zhu et al. (2022) both use IoT applications such as temperature and humidity sensors in global food supply chains. Both studies highlight the positive impact of IoT sensors on extending shelf life, reducing food waste and environmental sustainability.

  Differences: Luo et al. (2022) provide an in-depth analysis of several food categories and stages of the global food chain, presenting conservation consumption and food loss reduction, with a special focus on the role of sensors in environmental sustainability.

Together, the nine scholarly pieces offer a deep understanding of how technology and data-driven solutions are revolutionizing the different aspects of the food supply chain. These studies cover a wide range of supply chain domains, offering a rich tapestry of innovations, from RFID technology and smart packaging to wireless sensor systems and Internet of Things applications. We explore the similarities and differences between these research in this comparative study, grouping them into discrete themes to provide a thorough overview. In summary, despite the studies' varied approaches and topics, they all highlight how technology has the ability to fundamentally alter the dynamics of the food supply chain. The benefits to waste reduction, efficiency gains, and sustainability are shared, but the subtle differences in their strategies offer a comprehensive picture of the complex interplay between technology and the food industry's future.

5.1.7. Household stages

Mezzina et al.'s 2022 study on home food storage in Italy, which makes use of smart home technologies, highlights the serious consequences of improper food storage, as even a few hours of subpar preservation can drastically shorten the shelf life of food items. By increasing shelf life by almost 55% in adverse storage conditions, the suggested smart home system provides a creative solution that helps achieve sustainability, food waste reduction, and enhanced food safety objectives. However, since this is the only study found for the household stage during the literature review, comparison could not be done.

5.2. Limitations and challenges

Even though research done at different points in the food supply chain has provided insightful information about how technology and data-driven solutions can optimize processes, these studies also share certain common limitations and difficulties:

- Absence of precise quantitative data: A prevalent constraint among numerous studies is the deficiency of accurate quantitative data concerning the mitigation of food loss and waste (FLW) and its ecological consequences. Although these studies offer useful data on variables such as humidity, temperature, microbial composition, and environmental conditions, they frequently do not quantify the direct effect on the reduction of FLW and the wider environmental consequences.
- Variable focus: Rather than focusing on reducing FLW as their main goal, the studies frequently have different primary objectives, such as energy efficiency, microbial composition, or product quality. Although this diversity demonstrates the adaptability of wireless sensor systems across different food processing domains, it also makes direct comparisons of their FLW reduction results difficult.
- Restricted geographic scope: The results of some studies may not be as applicable to a global setting because of their narrow geographic focus, such as South Asia or Bangladesh. These regional studies do, however, also draw attention to the unique difficulties and possibilities that exist there.
- Lack of standardization: It can be difficult to develop standardized procedures for

FLW reduction and environmental impact assessment due to the use of various technologies, techniques, and sensors in different studies.

- Inadequate attention to consumer behavior: Research has shown that technology and data-driven approaches are crucial for lowering food loss while ignoring the part that consumer behavior plays in contributing to food waste throughout the supply chain. A more comprehensive approach to FLW reduction requires an understanding of and attention to consumer preferences and behaviors.
- Data handling and privacy issues: Using IoT and sensor technologies frequently necessitates managing enormous volumes of data. The issues surrounding data management, security, and privacy in the context of Internet of Things systems might not be adequately covered by these studies.
- The need for interdisciplinary collaboration: Experts from a variety of fields, including agriculture, food science, environmental science, and technology, must work together to address FLW and its effects on the environment. Occasionally, a multidisciplinary approach is absent from these studies.
- Possible unintended consequences: Using technology to improve the food supply chain may have unintended effects like higher energy usage or electronic waste from sensors. These factors need to be taken into account in subsequent studies.

Overall, even though the studies provide insightful analysis and creative solutions for enhancing different facets of the food supply chain, resolving the issues raised will be essential to maximizing the benefits of these technologies in terms of lowering food waste and minimizing their negative effects on the environment.

5.3. Implications (environmental, social, and economic aspects)

The synthesis of the results of different studies, each focusing on different stages of the food chain, provides a comprehensive overview of the profound effects of technology-based strategies on environmental, social and economic dimensions. Based on the nuanced details of each study, these implications illuminate the potential for integrating wireless sensor systems, Internet of Things technologies, and data-driven insights into various aspects of food production, storage, transportation, distribution, retail, and households.

5.3.1. Environmental effects

Saving resources:

- Siddiqui et al. (2021): An innovative approach to sustainable rice cultivation in Bangladesh shows a 90.91 percent reduction in water use compared to traditional methods, solving water scarcity problems and contributing to environmental sustainability.
- Feng et al. (2020): Effective methods of food preservation, as Badia-Melis et al. (2015) not only increases the conservation, but also reduces the environmental impact because fewer resources are needed for production, distribution and

disposal.

Energy efficiency:

- Baire et al. (2019): Variations in environmental conditions during bread making provide valuable information to optimize the process, reduce energy consumption and increase overall resource efficiency.
- Shih and Wang (2016): The use of wireless sensor systems in food production and retail significantly reduces energy use, which contributes to environmental sustainability and energy efficiency.

Reduce food waste:

- J. Zhu et al. (2022): The use of IoT sensors reduces food waste in commercial and transport situations, thus reducing the environmental impact of food production and disposal.

Smart packaging:

- Stramarkou et al. (2022): A comparison between Smart Packaging (SP) and traditional packaging (CP) emphasizes the importance of considering environmental protection and carbon footprint in packaging decisions. It presents a business analysis that talks about sustainable packaging options.

5.3.2. Social Effects:

Labor saving innovation:

- Zheng et al. (2021): Automation and technology-enabled processes in water quality monitoring solve labor shortages in the food industry, ensure business continuity and provide social benefits through technological innovation.

Food safety:

- Seo et al. (2016): Biosensors for bacterial detection significantly contribute to food safety, protect consumer health and increase trust in the food chain.

Consumer behavior:

- Vahdani and Sazvar (2022): Effective inventory management using dynamic pricing models and policies affects consumer behavior by reducing overproduction and excess inventory, which positively affects social practices related to consumption.

Innovation and employment:

- Tsang et al. (2018): The integration of technologies such as IoT sensors and digital twin technology in the food transport industry will stimulate innovation, create opportunities for economic growth and promote job creation in both social and economic aspects.

5.3.3. Economic effects

Cost reduction:

- Siddiqui et al. (2021): Sustainable rice cultivation methods significantly reduce rice production costs, making agricultural practices more economically viable, resulting in direct economic benefits.
- You et al. (2022): Efficient storage and distribution technologies bring significant savings to producers and consumers, which promotes economic efficiency in the supply chain.

Market access and business:

- Zhang et al. (2020): Improved transportation methods help food producers access new markets, increasing economic growth and incomes, expanding market access and business opportunities.

Supply chain performance:

- J. Zhu et al. (2022): IoT sensor applications to reduce food waste lead to a more profitable supply chain and bring financial benefits to companies that demonstrate financial efficiencies achieved through technology adoption.

Impact of Innovation:

- According to Stramarkou et al. (2022), choosing Smart Packaging (SP) over Conventional Packaging (CP) has economic ramifications, and the cost differences emphasize how important it is to take environmental factors into account when making packaging decisions. These insights can be very helpful for businesses trying to strike a balance between environmental and economic factors when making packaging decisions.

To sum up, this thorough examination of various studies highlights the complex effects of technology and data-driven strategies on the food supply chain. These tactics have the ability to develop a system that is more economically feasible, efficient, and sustainable. The studies do highlight the need for more research, practical application, and the development of standardized procedures in order to fully realize these advantages and guarantee a comprehensive overhaul of the food supply chain.

6. Summary

All the articles reviewed in this study and the findings are summarized in Table 3.

Table 3. Summary of Literature Review

Ref.	**Food Domain**			**Technology Domain**	**Country**	**Methodology**	**Findings**					
	Food Group	**Food Sub-Group**	**Supply Chain Stage**				**SL**	**FLW**	**Environmental**	**Social**	**Economic**	**Others**
(Pounds et al., 2022)	Meat	Pork	Storage	Smart packaging	USA	Experiment	Meat spoilage occurred after approximately 16 hours at 20˚C and around 28 hours at 4˚C.	N/A	N/A	N/A	N/A	A pH between 5.5 and 5.8 signals meat spoilage.
(Aguiar et al., 2022)	Milk, meat, fish, vegetables, fruits, and eggs	Horticultural products	Transportation	Wireless sensors system	Portugal	Experiment	N/A	N/A	N/A	N/A	N/A	The fluctuations in temperature and relative humidity reached up to 7.4 °C and 35.3%, respectively.
(Zhu et al., 2022)	1.Fruits, vegetables 2.Fruits, roots, tubers and plantains 3.Meat 4.Cereals, pulses, seeds and nuts, roots, tubers and plantai	Perishable and non-perishable foods	Planting, harvesting, processing, and marketing up to downstream treatments	IoT sensors	Global	Mathematical modeling and LCA	The SL is increased by around 33.6% for bananas, plantains and apples, 40.2 % for other fruits and vegetables, and 31.2 % for meat and animal products. The SLs are prolonged by 71–116 h, 57–94 h, and 65–85 h for bananas, plantains and apples, other fruits and vegetables, and meat and animal products, respectively.	Food losses are reduced by 25–41%, 20–33%, and 20–26% for the first three perishable food categories respectively. Food losses are inhibited in the storage and transport stages from an initial 50–58% to 5–7%. At the processing and wholesale stage, 27–33% reduction in FLs is seen.	Meat and animal products caused the highest environmental burden (per kg), which can reach 78 times higher than that of bananas, plantains, and apples on TER. Non-perishable food exhibits the least environment impacts except for TE, where that value for bananas, plantains and apples was 179 times lower than non-perishable food. Sensors application indicates leverage effect on 7 environment aspects in 10 indexes.	N/A	N/A	N/A

	ns											
(Marangon et al., 2022)	Fish	Fish	Storage	Smart packaging	Brazil	Experiment	The pH rose from 6.5 to 8.0 after 72 h, triggering color changes in the smart film from pale yellow to orange.	N/A	N/A	N/A	N/A	N/A
(Skawińska & Zalewski, 2022)	Milk, meat, fish, vegetable, fruits, and eggs	Perishable foods	Transportation	IoT sensors	Poland	Experiment	N/A	N/A	N/A	N/A	N/A	The temperature inside the truck rose from 12˚C to 18˚C and repeated opening of the truck door caused temperature increases (12˚C to 17˚C).
(Kilic et al., 2022)	Meat	Skinless chicken breast	Storage	Intelligent packaging and mobile App	Turkey	Experiment	Total viable count of chicken samples rose during the storage at 4˚C exceeding the critical level after 7 days of storage.	N/A	N/A	N/A	N/A	N/A
(Ma et al., 2022)	Meat	Chicken breast	Storage	Integrated smart packaging and deep learning technology	USA	Experiment	Total Volatile Basic Nitrogen of chicken rose during the storage at 4 ˚C exceeding the critical level after 96 h of storage.	N/A	N/A	N/A	N/A	N/A
(Jung et al., 2022)	Meat and milk	Pork and milk	Storage	IoT sensors	South Korea	Experiment	After 63 hours of storage, pork kept at 4˚C remained fresh, while the batch stored at 37˚C spoiled. Similarly, after 140 hours of storage, milk stored at 4˚C remained fresh, whereas the milk stored at 37˚C spoiled.	N/A	N/A	N/A	N/A	N/A
(Zhang et al., 2022)	Fruits	Strawberries, blueberries, plums	Storage and Distribution	Wireless sensors system	China	Experiment	Strawberry samples in FP and CMFP packaging spoiled after 7 days at room temperature, whereas those in the Ag-MOFs@CMFP packaging remained fresh. Unpackaged blueberries deteriorated on the 7th day, and plums on the 12th day, whereas packaged samples retained their appearance for a longer period.	N/A	N/A	N/A	N/A	The weight loss of the bare strawberries, blueberries and plums decreased by more than 45%, 27% and 15% after 7 days, while the weight of packaged ones remained over 70%, 85% and 95% of the original weight, respectively. The pH of strawberries in the control group increased up to 3.78 in a week, whereas the pH of strawberries packaged with Ag-MOFs@CMFP only increased up to 3.51. The same pH change trend occurs in blueberries and plums.
(Teixeira et	Fish	Gray shrimp	Storage	Smart packaging	Brazil	Experiment	The change in the color for the	N/A	N/A	N/A	N/A	N/A

al., 2022)							gray shrimp observed after 60 h of storage at 6 ˚C.					
(Yu et al., 2022)	Meat	Chilled broiler meat	Storage and Distribution	Smart packaging	China	Experiment	When MAP is used, the color change from bright yellow to light brown occurred at 6 days at 4°C while it occurred at 3 days and 12 h at 10°C and at 25°C, respectively.	N/A	N/A	N/A	N/A	N/A
(Lei et al., 2022)	Fish	Shrimp	Storage	Smart packaging	USA	Experiment	At 25°C, shrimps started turning from gray to red after 36 hours of storage. In contrast, when refrigerated at 4°C for the entire 72-hour storage period, they did not exhibit noticeable color changes.	N/A	N/A	N/A	N/A	N/A
(Ai et al., 2022)	Meat	Pork	Storage	Smart packaging	China	Experiment	The pH and TABC of pork stored at 4°C surpassed tolerable limits after 6 days. The TVB-N value reached its limit after 4 days, and the RPP10 film in the package turned a lighter shade of red, further confirming the loss of freshness in the pork.	N/A	N/A	N/A	N/A	N/A
(Zou et al., 2022)	Meat, fish, vegetables, and fruits	58 selected fresh foods, including major fruits, vegetables, meat, and fish	Retail (storage, distribution and sale)	Dynamic expiration date (DED)	China	Mathematical modeling	N/A	The DED mode reduced food waste by 10.02% at LT (0–8°C) but increased it by 15.94% AT MT (12–18°C) and 31.71% at HT (20–28°C). Under LT, it achieved a 15.99% reduction for foods with a 7-day shelf life, while under MT, reductions were 8.15% and 1.7% for foods with 120-day and 180-day shelf lives, respectively. However, under HT, the DED mode increased food waste by 57.49% for foods with a 7-day shelf life, compared to 17.87% and 9.86% for foods with 120-day and 180-day shelf lives, respectively.	N/A	N/A	N/A	N/A

(Si et al., 2022)	Fish	Shrimp	Storage	Smart packaging	China	Experiment	The results indicate that the shrimp spoiled after just 3 days of storage at 20°C.	N/A	N/A	N/A	N/A	N/A
(Shrivastava et al., 2022)	Fruits	Citrus	Transportation	Digital twin	South Africa	Mathematical modeling and experiment	Beyond 10 days of storage at ambient conditions, citrus showed excessive shriveling and became not sellable anymore. The mean value of $SL_{transpiration}$ was 10.3 days, while that of $SL_{respiration}$ was 8.5 days. This indicates that respiration driven shelf life was the limiting quality parameter for the citrus fruit.	Chilling injury observed in 2.5 – 4.2% of the fruit in the shipments during overseas maritime transportation from South Africa to various spots in the Northern Hemisphere (temperature changes between -1°C to 3°C for periods of 2 to 3 weeks).	N/A	N/A	The moisture loss ranged between 0.8% and 2.0%, with a mean value of 0.97% (Moisture loss lowers the sellable weight of the fruit so directly translates to a loss in profits).	The mean temperature of the fruit in these shipments was around -0.9 °C.
(Jaques et al., 2022)	Pulses, seeds and nuts	Soybean	Transportation	IoT sensors	Brazil	Experiment	N/A	N/A	N/A	N/A	N/A	The intergranular temperature decreased from 28-29°C to 28-27°C for group I while from 27.9-28.4°C to 27.5-28.2°C for group II. The RH of the air reduced from 84-85% to 82.5-83.5% for group I while increased from 95-98% to 97-99% for group II. The EMC increased from 10.05-10.07% to 10.9-10.1% for group I while decreased from 9.86-9.90% to 9.83-9.88% for group II. The CO_2 concentration changed between 338–550 ppm for group I while it increased from 1000 ppm to 3600 ppm, which might be an indication of spoilage, for group II. The dry material loss for both types of grains increased from 0 to 0.032%. (throughout 240 min.)
(You et al., 2022)	Fruits, Roots, tubers and plantains	Avocado, potato and apple	Storage and Distribution	IoT sensors and food simulators	Switzerland	Experiment	N/A	N/A	N/A	N/A	N/A	When comparing the seven-eighths cooling (SECT) for real avocado core with the core of the large version of the biophysical avocado, the difference was 3.0% while the comparison of half-cooling (HCT) and SECT for the small version revealed differences of 5.9% and 0.4%, respectively, which means the thermal response of the real avocados was captured by the biophysical one and the real avocados' thermal response was better than the small version. The large biophysical potato showed a consistent cooling time compared to the real potatoes, with an HCT difference of 1.4% and a SECT difference of 5.4%, which means the large biophysical potato captured the thermal responses of real

												large potatoes. Meanwhile, for small biophysical potatoes, both the HCT and SECT had a considerable difference compared to real potatoes. For apples, the temperature heterogeneities in a cooling chamber and applying only one sensor during this initial storage phase could be risky during the storage.
(Alexi et al., 2022)	Meat	Pork cutlets	Storage	Cadaverine biosensor	Denmark	Experiment	The agreement noted between the sensory freshness and microbial quality results indicate that the end of shelf life of the MAP pork cutlet's batch is between day 11 and day 13 of storage at 5 ◦C, which means shelf life can be extended by approximately 2–3 days with MAP considering assigned shelf life of pork is 9 days.	N/A	N/A	N/A	N/A	The cadaverine tissue concentration showed a strong correlation to the B. thermosphacta counts and a significant but not as strong correlation to odour freshness assessment scores while no other significant correlation was identified between cadaverine concentration and microbial counts.
(Yang et al., 2022)	Fish	Shrimp	Storage	Smart packaging	China	Experiment	The label color changed from brick red to orange-red after the shrimps were placed at 25◦C for 1 day and at 4◦C for 3 days. When the shrimps were placed at − 20 ◦C for 5 days, the label color barely changed. Also, the TVB-N measurements gave the same results.	N/A	N/A	N/A	N/A	N/A
(Luo et al., 2022)	1.Cereals, pulses, seeds and nuts, roots, tubers, plantains and their products 2. Vegetables, fruits 3.Meat, fish	1.Cereals, pulses, roots, oilcrops and others (n=29) 2.Fruits & vegetables (n=12) 3.Meat & animal products (n=13)	Harvest, producer, storage, transport, traders, processing, wholesale and retail	Several IoT applications (temperature and humidity sensors, wireless sensor network, etc.)	Global	Mathematical modeling and LCA	The consumption of SLs decreased due to improved food supply logistics by as much as 33.6±6.4% for bananas, plantains, and apples, 40.2±31.5% for other fruits and vegetables, and 31.2±18.7% for meat and animal products.Thus, ESLs(Effective shelf life) are prolonged by 71-116 h, 57-94 h, and 65-85 h for them respectively.	The FLs are reduced by 25-41%, 20-33%, and 20-26% for perishable bananas and apples, for perishable fruits and vegetables and for perishable meat respectively. And 5% for non-perishable cereals/pulses/starchy roots	N/A	N/A	For meat and animal products, sensors gave the highest leverage values achieving an 84% global carbon emission reduction. For fruits and vegetables, 6.7% of global carbon emission reductions were provided. Sensor model avg.	N/A

											emission per kg food is 1.3, 0.2 and -0.5 for manufacture, electricity and operation and treatment and recovery, respectively for Fruits and vegetables. It is 1.35, 0.2 and -0.5 for bananas, plantains, and apples and It is 1.35, 0.2 and -0.45 for meat and animal products whileIt is 0.35, 0.05 and -0.1 for non-perishables.	
(Mezzina et al., 2022)	N/A	N/A	Storage (at home)	Smart homes	Italy	Experiment	Poor conditions of food preservation can lead to a reduction of 4.72 days in the expiration day if left outside more than 3 h. Proposed system can lead to a reduction in the expiration day of only 0.08 days under good storage conditions while it can result in improvement of the food expiration date of ~55% under poor storage conditions.	N/A	N/A	N/A	N/A	N/A
(Kondjoyan et al., 2022)	Meat	Beef	Storage	IoT sensors	France	Mathematical modeling and experiment	Under 100% oxygen condition, SL increased from one to a few days at 2 °C. These few days of longer shelf-life until rejection remained when temperature was 10 °C. For an oxygen concentration of 20%, the fall in product temperature decreased its	N/A	N/A	N/A	N/A	Color variations were similar on untreated and decontaminated meat surfaces during the first 10–12 days of storage.

							exponential decay rate. These effects were more pronounced between 2 °C and 6 °C than between 6 °C and 10 °C. The increase in oxygen concentration from 20% to 100% had the same consequences when product temperature was 6 °C or 10 °C, whereas the effect of O2 was weaker when product temperature was 2 °C.					
(Leite et al., 2022)	Meat, Fish, Fruits	Beef, salmon, and strawberries	Storage	Smart packaging	Portugal	Experiment	With MO: BP 1%, for salmon and beef streak, the detection was only possible after 3 days, with noticeable color change to the naked eye, and a strong odor. Strawberry degradation, on the other hand, was detected after 10 days, and the presence of fungus was previously observed. On the contrary, for all the food samples under investigation, MO:BP 2% exhibited a total response to degradation within 2 days and the color change started to be seen within 24 h. At that point, there were no apparent signs of spoilage, either color, odor, and presence of microorganisms.	N/A	N/A	N/A	N/A	N/A
(Stramarkou et al., 2022)	N/A	N/A	Cradle-to-grave (food retail excluded)	Smart packaging	Greece	LCA	N/A	N/A	The carbon footprint of the CP (conventional packaging) is equal to 1.52 × 10−1 kg CO2eq., whereas the footprint of the SP (Smart packaging) is 59.7% higher. When considering the stages after the production of the packaging, the carbon footprint of CP became equal to 4.97 kg CO2 eq., whereas the footprint values of SP at the optimistic, realistic and conservative scenario are lowered to 3.93, 4.16 and 4.61 kg CO2 eq., respectively. When adapting the conservative scenario, the SP demonstrates improved environmental	N/A	The new innovative SP presents a total production cost of 0.23 EUR, which is 84.4% higher than the respective cost of CP.	N/A

									performance in 7 impact categories (negative rates), almost the same performance as CP in 6 categories (rates range: 0–1%) and worse performance in 5 categories (rates range: 4.7–13.0%).			
(Wei et al., 2022)	Milk, Meat, Fish, Vegetable, Fruits, Eggs	Perishable food	Retail	Dynamic lateral transshipment policy	China	Mathematical modeling	N/A	In terms of the amount of food wasted, the changing of approximation methods of the value function could not make a difference when the policy did not allow recycling. For the four policies except the PFP policy, the amount of food waste in the same scenario increases as the level of demand uncertainty increases. The more active and strict regulatory policies will lead retailers to adopt more effective inventory strategies and reduce the likelihood of food waste.	N/A	N/A	Among the tested policies (except PFP), the LFP policy performs best in terms of waste reduction, profit and cost control, especially in the scenario of high uncertainty level and stricter regulatory scenarios.	N/A
(Waimin et al., 2022)	Meat	Poultry	Storage	Wireless sensors system	USA	Experiment	The sensor tags were capable of wirelessly detecting spoilage in intentionally spoiled samples, showing shifts in the RF peak above the 20% threshold within 4 days while also remaining stable in contact with fresh samples displaying a minimal shift of ~5% after 10 days.	N/A	N/A	N/A	N/A	N/A
(Makarichian et al., 2022)	Vegetables	Garlic	Storage	E-nose	Iran	Experiment	According to the severity index of decay (DSI), day 8 is the best day for complete discrimination of infected samples; however, there was a possibility of initial diagnosis on day 4 (stored in low-density polyethylene (LDPE) bags at ambient temperature for 28 day).	N/A	N/A	N/A	N/A	N/A
(Vahdani & Sazvar, 2022)	Composite Dishes	Pasta salad	Retail	Dynamic pricing and inventory control policies	Iran	Mathematical modeling	Expected value of product waste can change between 0 to 30 based on initial inventory level and the intensity of social learning with dynamic pricing and	N/A	N/A	N/A	N/A	N/A

				under social learning			inventory control policies under social learning and waste reduction can be provided. The waste avoidance becomes more evident when the intensity of social learning, k, increases, and also the product waste increases by the higher initial inventory levels because they limit the flexibility of the ordering and pricing decisions.					
(Giarratana et al., 2022)	Fish	Atlantic mackerel	Storage	A mathematical model based on dynamic temperatures conditions	Italy	Experiment	During 12 days of storage, a critical value of 6 Log cfu/g of spoilage bacteria associated with a significant decay of the sensorial characteristics was exceeded after 9 days of storage for Group A (at a constant temperature of 1 °C) and 3 days for Group B (a fluctuating temperature ranging between 1- 7°C).	N/A	N/A	N/A	N/A	N/A
(Zhu et al., 2022)	Vegetables	Garlic scape	Transportation	Wireless sensors system	China	Experiment	N/A	The garlic scapes quality loss decreased from 20–30% to 15%.	N/A	N/A	The market price of fresh garlic scapes in Tianjin increased from below 5 yuan/kg to above 10 yuan/kg	Max. Vol. Fr. of Ethylene= 2.95 ppm Max. CO2 Conc.=2.6% Max. Temperature= 22.6 C Max. Relative Humidity= 92.0% Water content decrease=2.1% SSC increase=6.12% (700 km transportation under cold storage, from Zhongmu to Tianjin)
(Torres-Sanchez et al., 2021)	Vegetables	Lettuces	Storage and Distribution	Wireless sensors system	Spain	Experiment	N/A	N/A	N/A	N/A	N/A	At the set setpoint temperature, at 10°C, temperature changed between 10.20°C-10.62°C while at the set setpoint temperature, at 5°C, temperature changed between 4.52°C-5.30°C and at the set setpoint temperature, at 2°C, temperature changed between 1.98°C-3.00°C during a month.
(Siddiqui et al., 2021)	Cereals	Rice	Manufacturing	Wireless sensors system	Bangladesh	Experiment	N/A	N/A	The design saves about 90.91% of water when transporting it from the source using plastic piping instead of earthen canals. Compared to the traditional method, the proposed automated system is expected to require less energy.	N/A	The AWD automation scheme proposed in this paper is expected to reduce irrigation costs further since it uses plastic pipes to carry water.	N/A

(Aytaç & Korçak, 2021)	Composite dishes	Fast-food	Retail	IoT for Quick Service Restaurants	Turkey	Experiment	N/A	After implementation in two pilot restaurants for a week, about 10% reduction of food waste was achieved.	N/A	N/A	N/A	N/A
(Zheng et al., 2021)	Beverages	Water	Manufacturing	Wireless sensors system (Zig Bee)	China	Experiment	N/A	N/A	N/A	N/A	N/A	Microbial concentration assessment results between 7 groups involving flora, fungus, germ and bacteria reveals that concentration changes between 0.30-0.35 for flora, 0.10-0.20 for fungus, 0.23-0.32 for germ and 0.10-0.20 for bacteria.
(Nair et al., 2021)	Fruits	Banana	Storage	E-nose	India	Experiment	N/A	N/A	N/A	N/A	N/A	For 3000 samples over a period of 2 days, gas concentration changed from 0.083 to 1.0 ppm, while temperature and humidity changed between 0-1.0
(Sharif et al., 2021)	Beverages	Spring water	Storage	Radio Frequency Identification (RFID) and Machine Learning	UK	Experiment	N/A	N/A	N/A	N/A	N/A	The food contamination/contents were sensed with an accuracy of 90% for water bottles samples having a different quantity of salt and sugar.
(Catania et al., 2020)	Spices and condiments	Aromatic herbs (Sage and Laurel)	Manufacturing	Wireless sensors system	Italy	Experiment	With the drying method, the two species showed a different microbial stability and, consequently, had a different shelf life, longer for sage than laurel, as also confirmed by water activity values (The moisture content was lower than 14% for sage and 32% for laurel.)	N/A	N/A	N/A	N/A	N/A
(Wang et al., 2020)	Fruits	Blueberries, sweet cherries, apples	Transportation	Wireless sensors system with Multi-Strategies Control	China	Experiment	N/A	N/A	N/A	N/A	Apple Experiment (Ethylene Multi-Strategies Control: 1-MCP): No difference in the weight loss rate. Apple Experiment (Ethylene Multi-Strategies Control: MAP (20% CO2)): Apples in the MAP had lower	Blueberry Experiment: The ethylene content (<5 ppm) at 0 °C and at 5 °C was far lower as compared to at 22 °C (>25 ppm). The blueberries at 22 °C showed the lowest firmness (3.88 kgf) and the highest spoilage (17.65%) after 7 days, while the SSC and pH showed no significant difference among the three groups. Sweet Cherries Experiment: the ethylene content in Group I (ambient temperature) was higher than that of the other two groups during the entire experiment period, which was 25 ppm while it was 20 ppm and 10 ppm for Group II (ice packs were placed in each package) and Group III (precooling at 0–1 °C for 12 h) respectively at the end of 7 days. The sweet cherries in group I showed the lowest firmness (4.3 kgf) and the highest spoilage (32.0%) after 7 days, while the SSC and pH showed no significant difference among the three groups.

											weight loss rates, which is 64% respectively than that of the control group.	Apple Experiment (Ethylene Multi-Strategies Control: 1-MCP): The released ethylene rate in the control group showed an upward trend, while the released ethylene rate in the experimental group almost remains at 0 ppm/h level since the 1-MCP inhibited the ethylene synthesis. After 24 days, apples with 1-MCP treatment maintained higher firmness (8.17% higher), lower soluble solid contents (4.80% lower) and a higher ΔE value (8% higher). Apple Experiment (Ethylene Multi-Strategies Control: MAP (20% CO2)): The ethylene emission rate in the experimental group dropped sharply after putting into 20% CO2 MAP, and reached the lowest value (0.5 ppm/h) on the 3. day, then remained still. Also,apples in MAP could maintain higher firmness and ΔE, on average 1.65% and 6.82% respectively higher than that of the control group.
(Feng et al., 2020)	Fish	Shellfish	Storage	Wireless sensors system (Blockchain based)	China	Experiment	N/A	N/A	N/A	N/A	The samples underwent 0.12% loss of initial weight, and ending at 0.40 % (at −18◦C for 80 hours)	The temperature changed from −23.2 C to −20.1. In the beginning, humidity changes slowly, next has a small drop, then rises to 40.2%. The concentration of CO2 and O2 rose from 178.13 ppm to 6965.62 ppm and from 20.87% to 32.37%. (at −18◦C for 80 hours)
(Zhang et al., 2020)	Fruits	Sweet cherry	Transportation	Dynamic monitoring and quality assessment system (DMQAS)	China	Experiment	N/A	N/A	N/A	N/A	The market price of fresh sweet cherries increased by about 50% (the market price increased from about 40 yuan/kg to 60 yuan/kg)	The mean temperature and relative humidity of these three groups was 24.8 °C and 83.6% (Ambient temperature group), 22.2 °C and 76.15% (Ice-added group), 18.5 °C and 74.60% (Pre-cooling group) The color of sweet cherries changed from from bright red to deep red while pH changed from 3.58 to 4.40, which meant the taste of sweet cherries became unpalatable and they became soften (hardness changed from 5.62 to 4.30) and the value of SSC changed from 17.06% to 13.27%. The quality loss rate decreased by 10%–15%. (the express logistics for 10 hours)
(Torres-Sánchez et al., 2020)	Vegetables	Lettuces	Storage and Distribution	Wireless sensors system	Spain	Experiment	N/A	N/A	N/A	N/A	The weight loss was greater on the last sampling day for each temperature,	The physicochemical parameters of Iceberg lettuce stored at different temperatures (2 °C, 5 °C, 10 °C, 15 °C and 20 °C) during shelf life are measured. No remarkable differences in TA were found between the initial and last day of storage at each temperature. A decrease of 24% and 23.1% in SSC at 5 and 2 °C

											reaching 4.0/1.64%, 3.4/1.4%, 2.4/1.26%, 2.1/0.65% and 2.2/2.9% at 20 °C, 15 °C, 10 °C, 5 °C and 2 °C respectively (29 days storage)	respectively and although the TA remained constant, the pH increased by 4.0% at 5 °C was observed during 21 and 29 days storage, respectively. Land Transportation Trials: transportation in germany shows a three-day trip with a set-point temperature of 4 °C, as in the Netherlands, but with a bigger temperature fluctuation (2.9 °C-7.6 °C) while in the netherlands, there are temperature differences of up to 3.8 °C.Transportation in UK shows less temperature difference and in Belgium, the variation is the most significant compared to the others (temperature drop of 3.2 °C from the set-point temperature of 7 °C)
(Urbano et al., 2020)	Vegetables, Fruits	Pumpkin and oranges	Transportation and retail	RFID tags	Spain, Colombia	Experiment	N/A	N/A	N/A	N/A	N/A	Pumpkin Experiment: Chamber and selling point: 3.2–5.2°C for 14.96 days. Transport: 5.8–8.4°C for 6.86 days Manipulation time: 9–22°C for 3.99 h Orange Experiment (oranges sent from Valencia to Cork during 8.8 days.): the lowest temperature registered was 1 °C, and the lower breakpoint was never reached (below −5 °C), so no cold chain break was detected.
(Feng, et al., 2020)	Fish	Salmon	Storage	E-nose	China	Experiment	N/A	N/A	N/A	N/A	N/A	There was a significant change in the TPA of salmon meat stored at 6 °C for 14 days and in the hardness at 4 °C during the first 9 days of storage time. However, there was no significant change in the hardness at 0 °C during the first 6 days of storage time. There was a significant change in the chewiness at 4 °C after 3 days of storage time and stored at 0 °C and 6 °C for 14 days and in the springiness, cohesiveness and gumminess and resilience 0 °C and 4 °C after 3 days of storage time. pH decreased in the first 3 days and sensory properties were satisfactory and then, pH increased showing bad acceptance (at all temperatures). .
(Ramírez-Faz et al., 2020)	Milk, Meat, Fish, Vegetables, Fruits, Composite dishes	Dairy products, charcuterie, meat, and frozen products	Storage and retail	Refrigerated Cabinets with IoT sensors	Spain	Experiment	N/A	N/A	N/A	N/A	Losses of 1500 € were prevented.	Temperature changed between 2-15 °C for charcuterie and between 6-15 °C for dairy products during the day (Set point temperature is 2°C).

(Banga et al., 2019)	Pulses, seeds and nuts	Chickpea,Green gram	Storage	An insect detection probe	India	Experiment						Average relative humidity and temperature observed in chickpea infested with C. chinensis and C. maculatus were 40.60%, 27.59 °C and 54.64%, 27.10 °C, respectively, while the ambient RH and temperature were 68% and 30 °C, respectively. In the case of green gram, the RH and temperature with C. chinensis and C. maculatus were 33.20%, 26.86 °C and 33.20%, 27.16 °C, respectively, while the prevailing ambient RH and temperature were 60% and 37 °C, respectively.
(Feng et al., 2019)	Fish	Shellfish	Storage and Distribution	Wireless sensors system	China	Experiment, Mathematical equation	The shelf life of real cold chain transportation (−9.6 °C), supermarket display (−17.4 °C), refrigerator storage (−12.4 °C) were estimated to be 290.05 days, 546.05 days, and 398.47 days, respectively.	N/A	N/A	N/A	N/A	The quality loss of real cold chain transportation (−9.6 °C), supermarket display (−17.4 °C), refrigerator storage (−12.4 °C) were estimated to be 48.26%, 2.59% and 28.92%, respectively.
(Jara et al., 2019)	Milk, Meat, Fish, Vegetable, Fruits, Eggs	Perishable food	Transportation	IoT sensors	Ecuador	Experiment	N/A	N/A	N/A	N/A	N/A	The coldest temperature is obtained near the walls, ceiling and floor. The stabilization temperature (0°C) can be observed after 2400 s, while the stabilization of the system is achieved in the time of 7200 s.
(Baire et al., 2019)	Cereals	Bread	Manufacturing	Wireless sensors system	Italy	Experiment	N/A	N/A	N/A	N/A	N/A	The temperature during the kneading and first leavening is far from the recommended value of 28°C. The average temperature in the leavening room is higher; i.e., 28.62 °C (32% higher). The temperature values in this step of the process are closer to the prescribed value of 32°C for almost every day of processing. The average value of relative humidity in the kneading room is 59.98%, whilst in the leavening room it is 61.26%. The average humidity values during these phases are about 50% higher than the prescribed level. The CO recorded during different days, in January and August, present very different values (30.42 ppm versus 9.29 ppm) and their patterns are rather different. During the leavening, the daily average is 620.26 ppm, whilst, before, the CO2 varies around the value of 813.257 ppm.
(Jilani et al., 2019)	Meat	Broiler carcass (PSE class vs Normal Class)	Storage	Wireless sensors system (microwave sensing system)	Pakistan	Experiment	N/A	N/A	N/A	N/A	N/A	Ph decreased from 6.9 to 5.9 for normal class while it decreased from 6.8 to 5.7 over the duration of 1 h–8 h. Dielectric measurement: Normal quality meat showed a higher shift than PSE meat and the difference observed between these resonance

												frequencies was 35 MHz (about 5.5% difference).
(Tsang et al., 2019)	Meat, Fruits	Perishable food	Storage	A blockchain–IoT-based food traceability system (BIFTS)	China	Experiment	N/A	N/A	N/A	N/A	N/A	The results of quality decay from fuzzy food quality management for the five selected perishable foods reveals that normalized food quality of food type 1 decreased more than 90% in 4 days while it was 65 days and 90 days for food type 2 and food type 3 respectively, Normalized food quality of food type 4 and 5 did not fall below 90% in 100 days.
(Popa et al., 2019)	Vegetables	Onion	Storage	Wireless sensors system	Romania	Experiment	N/A	N/A	N/A	N/A	N/A	Onion in the Vacuum Container: In the reference experiment (empty container), the gas sensor output quickly jumped to 3 V. The gas sensor presented large fluctuations during the first 2 h after being introduced in the vacuum container. Then, its output stabilized at around 1 V, which means CO and alcohol, both volatile organic compounds specific to onion decay, were being measured. Also, the humidity increased by 30% of the initial value in the onion-filled container, which showed that the onion produces vapors. (during 5 h, at 27 °C)
(Tsang et al., 2018)	Meat, Fish, Vegetable, Fruits,	Meat, Frozen and fresh food	Storage and Distribution	Internet of Things (IoT)-based risk monitoring system (IoTRMS)	China	Experiment, Mathematical equation	Estimation of shelf life and rate of quality degradation for fresh meat: Average temperature (°C) is −8.3, −3.8, −6.9 and −0.7 while Shelf life (days) is 7, 5.4, 5.4 and 4.3 and, rate of quality degradation is −14.3, −18.5, −18.5 and −23.26 for Supplier (S), Processor (P), Distributor (D) and Retailer (R), respectively.	N/A	N/A	N/A	N/A	After implementing IoTRMS, the accident frequency rate recorded an improvement with 60% in the reduction of the number of accidents and injuries. However, the idle time for recovery is slightly increased by 25%. The order fulfillment rate showed 14.1% improvement. The workforce stability was improved by 13.1%. (warehouse temperature = 2°C)
(Tsang et al., 2018)	Fruits, Vegetables	Apple, Grapefruit, Mango, Melons, Tomatoes	Transportation	Internet of Things (IoT)-based route planning system (IRPS)	Hong Kong	Pilot study	N/A	The food spoilage rate decreased from 22.6% to 7.9%, a reduction of 65%. Thanks to appropriate packaging settings, the number of return deliveries due to food spoilage and cargo discrepancy was greatly reduced by 63.6%.	N/A	N/A	The company only requires 8.2 months to get back the money invested.	Since the IRPS provides efficient delivery routes and appropriate packaging settings for the products, customer complaints reduced from 8 to 3 times, a decrease of 62.5% and the overall customer satisfaction increased from 6.5 to 8.3 points, a 27.7% increase. For operational efficiency, the on-time performance on the fulfillment of orders increased from 56.8% to 86.1%.
(Wang et al., 2018)	Fruits	Holly	Harvesting, Storage, Transportation,	Wireless sensors system	China	Experiment	N/A	N/A	N/A	N/A	The market price increased from below 20	The quality loss of fresh-cut branches of North American holly decreased from 25% ~ 30% to below 15%. (transported from Weihai after harvesting to Beijing. about 2.5 days and about 800.6 km) The temperature during

			Retail, Sale							yuan/bundle to above 50 yuan/bundle. (bundle=ten branches)	harvesting (S1) varied between 13.8 -19.8 °C. In the cold transportation (S2), between 18 -16.2 °C and decreased from 16.1 °C to 9.5 °C in the precooling (S3). During the packaging (S4), the temperature rose quickly and decreased 8.7 °C in the storage (S5). During ordinary transportation process from Weihai to Beijing (S6), the temperature raised from 7.2 °C to 11.7 °C and in the sale (S7) varied with ambient temperature. In the S1, S2 and S3 stage, the relative humidity rose and In the segment S4 and S5, had a small fall at first then rose slowly. It rose slowly as a ladder in the segment S6 and was stable at first in the segment S7, then decreased quickly. In the whole process, the average concentration of ethylene was 12.59 ppm, and the max volume fraction of ethylene was 22.06 ppm. And the max volume fraction of CO2 is 6949.5 ppm, and the min volume fraction of CO2 is 413.25 ppm. Before segment S2, the respiration rate is rising with average value and maximum value are 164.61%·kg−1·min−1·L−1 and 396.14%·kg−1·min−1·L−1, then it remained in stationary phase until segment S4. Moisture content was measured as following: 61.67% (Before S1), 55.62% (After S1), 54.05% (After S2), 48.16% (After S3), 47.22% (After S4), 46.93% (After S5), 40.72% (After S6), 36.16% (After S7).
(Wang et al., 2018)	Fruits	Peach	Harvesting, Storage, Transportation, Retail, Sale	Multisensors-managed traceability system	China	Experiment	N/A	N/A	N/A	N/A	N/A	Weight loss: 3.48% (in the Shandong-Singapore export chain) The quality loss of honey peach export chain decreased from 25% to 30% to below 13%. Decay rate=6.5% Flesh firmness decline rate=61.62% SSC decline rate=1.41% The temperature varied from 12.9 °C to 28.3 °C during harvesting (S1). During, the short transportation (S2) from the orchard to the refrigeration house, it was 14.88 °C. During the precooling (S3) process, decreased from 13.8 °C to 6.5 °C and reduced from 6.5 °C to 3.6 °C in cold storage (S5). In the subpackage (S6), the temperature rose from 3.6 °C to 5.8 °C. During the refrigerated transportation process (S7), varied greatly, between 1.4 -6.7 °C. In the temporary storage for display and sale (S8), the temperature was ranged from 1.3 °C to 3.1 °C. The RH ranged from 53.90 %RH to 70.90 %RH in the S1. In

												the S2, the RH gently increased to 78.21 %RH. In the S3, the RH fluctuates sharply, with the maximum value 92.4 %RH. The RH decreased slightly in the brushing and sorting (S4), with the average value 67.27 %RH. In the S5, the RH raised from 68.30 %RH to 77.80 %RH. The RH continuously rose to 86.40 %RH and 95.8 %RH in the segment S6 and S7 as well. In the segment S8, the RH fluctuated greatly from 94.19 %RH to 99.90 %RH. The ethylene peak occurred in the segment S3 and segment S7 (12.92 ppm). After S7, the volume fraction of ethylene declined sharply, and at last, the ethylene maintained a balance from 0.16 ppm to 0.83 ppm. The effective volume fraction of O2 varied from 19.16% to 20.31% in all the segments. The effective volume fraction of CO2 varied from 0.14% to 0.87% in the whole segment of the honey peach export chain.
(De Venuto & Mezzina, 2018)	Vegetables	Tomato	Storage	Wireless sensors system	Italy	Experiment, Mathematical equation	There was an improvement of the expected expiration date of about 1.2 ± 0.5 (15% of maximum product useful life) days, for each pallet, when placed in a non-refrigerated environment. (monitored for about 10 days and 11 h)	N/A	N/A	N/A	N/A	N/A
(Tervonen, 2018)	Roots, tubers, plantains	Seed potatoes	Storage	Wireless sensors system	Finland	Experiment	N/A	N/A	N/A	N/A	N/A	Temperature changed between -5°C and 5°C while relative humidity changed 50% and 96%in the warehouse during 70 days.
(Jedermann et al., 2017)	Fruits	Banana	Transportation	Intelligent Container	Germany	Mathematical Modeling and Experiment	At the end of the transport, the predicted green life for two boxes (test in 2009 with a 12-year-old container, and in 2012 with a one-year-old container) varied by 7.3 days (~2 weeks trans-oceanic transport).	N/A	N/A	N/A	N/A	For a 12-year-old cooling unit, the average temperature was ~2.5 °C higher than for a new Thermoking cooling unit. Before opening of the air flap, CO2 increased by 0.086% per hour, equivalent to a production rate of 4.5 g/(t·h) for a free air volume of 47.4 m3 and a total load of 17.6 tons. During ripening, the CO2 production increased by a factor of 10 to 46 g/(t·h)
(Xiao et al., 2017)	Fruits	Grapes	Harvesting, Transportation, Storage and Distribution	Wireless sensors system	China	Experiment	The shelf life was 56 days when predicted and 58 days when measured for grapes based on firmness (storage at 0°C) and it was 52 days when predicted and 56 days when measured for grapes based on moisture loss rate(storage at 0°C).	N/A	N/A	N/A	N/A	The maximum range of temperature fluctuation is about 30°C when the table grapes were harvested and sold, while the minimum range is about 0°C when stored and transported. A reduction of firmness by 50% occurs after 53 days of storage at 0°C, while at 30°C the same level of reduction is observed in only about 3 days. These decaying processes occurred in 3 days during storage at temperatures of 20°C, 25°C or

											30°C, while at 0°C the same phenomena only occurred after 50 days of storage. The TSS content did not show significant differences at 20°C, 25°C, and 30°C in 6 days, and rose to the maximum level in 9 days and then decreased in the case of 10°C.
(Tsang et al., 2017)	Meat, Fish, Vegetables, Fruits, Beverages, Milk	Meat, seafood, vegetables, fruits, wine and dairy products	Storage	Wireless sensors system	Hong Kong	Mathematical Modeling	N/A	N/A	The electricity consumption is estimated with a 10.4% reduction on average if temperature is reduced by around 2°C, and the humidity is increased by around 10% during these 10 working days.	N/A	N/A	The average temperature and humidity during these 10 days were −2.045°C and +9.64%,, respectively. It is implied that the storage temperature should be reduced by around 2°C, and the humidity should be increased by around 10% to meet the best handling requirements of environmentally sensitive products (ESPs). The number of complaints is reduced from 8 to 2, while the order fulfillment rate and satisfaction rate recorded 5.45% and 17.33% increments, respectively. On the other hand, the product obsolescence rate for handling ESPs has decreased from 13% to 8% of total number of handled ESPs.
(Musa & Vidyasankar, 2017)	Fruits	Blackberry	Storage and Distribution	RFID	Canada	Experiment	Due to the delayed action, 30% of the pallets suffered from shelf life loss without fog nodes.	N/A	N/A	N/A	N/A	N/A
(Seo et al., 2016)	Fish	Raw fish,shellfish	Retail	Wireless sensors system (biosensor)	South Korea	Experiment	N/A	N/A	N/A	N/A	N/A	For the raw fish, the two (EOC sensor vs standard protocol) methods showed identical performance in that only the samples inoculated with 100 CFU of the bacterium were consistently positive. For the shellfish, both assay results revealed more sensitive performance than those for raw fish in that the samples inoculated even with 10 CFU of the bacterium expressed only partially positive results. Among 5 repetitive analyses for the same food sample, the positive results reached 80% using the standard protocol and 40% using the EOC sensor. 10 CFU bacteria inoculated in the real samples established the minimum border titer detectable using the EOC sensor with the detection limit of 1.4 × 104 CFU/mL.
(Shih & Wang, 2016)	Composite Dishes	Braised pork rice	Production, storage, transportation, and retail	Wireless sensors system	Taiwan	Mathematical Modeling	N/A	N/A	The consumption of electrical power in the central kitchen was reduced, to contribute turnover from US$14.23 raised to US$18.64 per kilowatt hour. Likewise, it was also used	It produced 150 job opportunities.	The yearly energy cost of cooling has been reduced about 10% while annual sale of	N/A

									in stores to contribute turnover from US$4.32 raised to US$4.58 per kilowatt hour.		braised pork rice has been enhanced by 36% (from 4.44 million bowls in 2009 to over 6 million bowls in 2010)	
(Thakur & Forås, 2015)	Meat	Chilled lamb products	Transportation	RFID	Norway	Experiment	N/A	N/A	N/A	N/A	N/A	Product temperature during transportation (800 km,36 h) changed between -0.8°C and 2.7°C while the ambient temperature inside the truck changed between -1.7°C and 2.8°C. The ambient air temperature changed between -1.7°C and 24°C.
(Badia-Melis et al., 2015)	Fruits, Pulses, seeds and nuts	Citric fruits and different varieties of nuts	Storage	A combination of RFID and Wireless sensors system	Spain	Experiment	N/A	N/A	N/A	N/A	N/A	The temperature differences between the max. and min. were around 5 °C and were higher than inside the room (around 3 °C). Both the inside node and the outside node present very similar lower H (equal to 4 kg water/kg dry air), while the upper H reaches more than 12 kg water/kg dry air in the outside node, and inside does not go beyond 8 kg water/kg dry air. In this case the air inside has an H oscillating in a smaller range (between 4 and 8 kg water/kg dry air) than in the outside (between 3 and 10 kg water/kg dry air), and a much wider range of temperatures than the other two chambers (because the room was open during long periods of time), it even reaches 23 °C in the node outside. In some occasions the RH reaches 80% whereas outside it never goes above 55% despite the door usually being open.
(Aung & Chang, 2014)	Fruits	Banana	Transportation	Wireless sensors system	South Korea	Experiment, Mathematical equation	Relative shelf life calculation results: 100% shelf life (at 13°C-16°C), 79.68% shelf life (at 16°C-19°C) and 62.89% shelf life (at 19°C-22°C).	N/A	N/A	N/A	N/A	Average rate of CO2 emission calculation results: 9.63 ppm/min (at 13°C-16°C), 12.09 ppm/min (at 16°C-19°C) and 15.35 ppm/min (at 19°C-22°C).
(Eom et al., 2014)	Meat	Pork	Storage and Distribution	RFID	South Korea	Experiment	Use by date = 12.029 hours under 22°C Use by date = 181.28 hours under 4°C Use by date = 50.47 hours under initially 4°C and then under 22°C for 10 hours and then 4°C	N/A	N/A	N/A	N/A	N/A
(Hafliðason et al.,	Fish	Cod	Transportation	Wireless sensors system	Iceland	Experiment	The impact of the higher average temperature for the abused pallet P2: 0.7 ±1.01°C compared to P1:	N/A	N/A	N/A	N/A	The pallet under normal temperature conditions maintained temperature close to 0°C. The max. difference in ambient

2012)							2 0.2 ±0.15°C resulted in about a one day loss of shelf life.					temperature in the container was 18°C, which occurred just after loading (overall average difference of 6.9°C). A temperature gradient was also observed for the ambient temperature surrounding the pallet (max. 5.7°C) during the abuse period, with an overall average difference of 0.84°C. During the abuse period the product temperature increased at 4°C. The largest temperature difference of products in the EPS boxes occurred during the abused period where the temperature difference was 5.2°C (shipping, handover and trucking) The selection of a too low criterion for product temperature as suggested by industry experts (20.5°C to 0.5°C) showed that the number of false alerts would have been very high, while a more lenient temperature criterion (1°C) generated fewer and more relevant alerts.
(Wang et al., 2010)	Milk, Meat, Fish, Vegetable, Fruits, Eggs	Perishable food	Transportation	RFID	Hong Kong	Mathematical Modeling	N/A	Using the rules set for that case to reschedule the vehicles and the containers reduced the transportation losses of perishable products to 50% in a particular accident.	N/A	N/A	N/A	N/A
(Ruiz-Garcia et al., 2008)	Fruits	Fruits	Storage and Distribution	Wireless sensors system	Spain	Experiment	N/A	N/A	N/A	N/A	N/A	For Xbow: RH is between 62.1% ± 0.7 and 67.6% ± 2.1 while temperature is between 8.40°C ± 1.1 and 9.06°C ± 0.3. For Xbee: RH is between 84.1% ± 2.1 and 86.0% ± 3.3 while temperature is between 3.60°C ± 0.3 and 3.71°C ± 0.4.

7. Conclusion

To sum up, this compilation of research studies that look at technology-driven solutions at different points in the food supply chain offers a thorough picture of the diverse ways that technology is used to address important problems like product quality assurance, sustainability, and food loss and waste (FLW). The combined findings of these studies highlight how technology has the ability to transform the way that food is produced, stored, transported, distributed, and handled. Even though every study is different and concentrates on different goals, a number of themes come up that highlight the significance and influence of technology throughout the whole food supply chain.

These studies reviewed highlight the critical role that technology plays in mitigating FLW. Innovative solutions enable real-time monitoring, precise environmental control, and early spoilage detection, from wireless sensor systems to Internet of Things (IoT) devices. As such, these technologies contribute to food safety and quality assurance, waste reduction, and product shelf-life extensions. The research highlights the significance of technological advancements in enabling early detection, quality preservation, and inventory optimization at various stages of the supply chain.
These studies also emphasize the important economic and environmental effects of technology-driven solutions. Businesses can cut production costs, preserve resources, and lessen their carbon footprint by reducing FLW. To improve the sustainability of food production and distribution, technology is also essential.

The necessity of individualized strategies for various food categories is another crucial lesson to be learned from these investigations. Because different foods respond differently to different storage and transportation environments, tailored, data-driven strategies are essential to preserving product quality. The wide range of food products examined, from grains and meats to fruits and seafood, highlights how adaptable technology is in tackling the particular problems that each food category faces.

These studies also highlight how crucial it is to take market dynamics and consumer behavior into account. Retailers can maximize sales and reduce waste by integrating dynamic pricing models and customer preferences. This emphasizes how dynamic food supply chains are and how crucial it is to adjust to shifting market conditions.

These studies have significant contributions, but they also have drawbacks, like narrow geographic scopes and inconsistent focuses. It is common for researchers to have primary goals that are not directly related to FLW reduction, such as energy efficiency, microbial composition, or product quality. Furthermore, the regional focus of certain studies may restrict the applicability of the results in a global setting. These difficulties, however, also offer chances for more situation-specific answers and case studies that can direct further investigation and real-world implementations.

All things considered; these studies' combined results offer a thorough grasp of how technology is changing the food supply chain. They highlight how different phases of food production and distribution have the potential to reduce food waste, promote sustainability, and enhance product quality. As technology develops further, food industry stakeholders can use these insights to build more customer-focused, sustainable, and efficient supply chains. This will help ensure that food is always safe, fresh, and environmentally friendly in the future—all while satisfying the world's growing need for sustenance.

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