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RESEARCH ARTICLE

Industry 4.0 Technologies in Circular Food Supply Chains: A Systematic Literature Review

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Abstract

This paper explores the transformative role of Industry 4.0 (I4) technologies—specifically Blockchain, Internet of Things (IoT), Artificial Intelligence (AI), Big Data Analytics (BDA), Smart Factories, Robotics—in enabling the circular food supply chain (FSC). Through a systematic literature review, we identify how these technologies contribute to key circular economy (CE) strategies in FSC, comprising reduction, redistribution, valorisation, and nutrient recovery. We also examine implementation barriers, including digital infrastructure gaps, regulatory misalignments, and data interoperability. A conceptual framework is proposed to map digital solutions to CE principles in food systems. Our findings offer actionable insights for scaling up digital-enabled circular practices in the agri-food sector.

Keywords Industry 4.0 (I4) · Food supply chain (FSC) · Circular economy (CE) · Sustainability · Food Waste · Blockchain · Internet of Things (IoT) · Artificial Intelligence (AI) · Big Data Analytics (BDA) · Smart Factories · Robotics.

1. Introduction

According to the latest estimates from the United Nations Environment Programme (UNEP) and the Food and Agriculture Organisation (FAO), approximately 1.05 billion tonnes of food were wasted globally in 2022. This equates to nearly 132 kilograms per person and represents about 19% of all food available to consumers. The economic impact of this waste is substantial, with global losses estimated at around USD 1 trillion annually (FAO, 2023). The food supply chain (FSC) is one of the least efficient sectors as it generates losses at all levels, including production, processing, transporting and storage, sales, and consumption (Ojha et al., 2020)

Food wastage is generated at different stages. Food loss occurs in the upstream stages of the FSC, during the production or manufacturing phases, while food waste occurs at the downstream stages, at the retail and consumer levels (Latino et al., 2021). Around 13 percent of food produced is lost between harvest and retail, even before it reaches the consumers (Govindan, 2018). The increased demand for food is compelling the food industry to explore more efficient ways to prevent food wastage, as the increased production has led to increased use of resources, generating more significant waste within the upstream stages of the FSC (Govindan, 2018).

Reducing food wastage can lead to increased economic efficiency and productivity, food security, and resource and energy conservation, addressing the reduction of GHG emissions. Reducing food loss is significant to the food industry to improve competitiveness, resilience, and sustainability. While policies bolstering awareness, behavioural change, and improving managerial practices are of great importance to achieving this goal, technologies can provide support and practical solutions. Adopting Industry 4.0 (I4) digital

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technologies, encompassing blockchain, Internet of Things (IoT), artificial intelligence (AI), big data analytics (BDA), smart factories and robotics to analyse the contribution of these technologies to economic, social and environmental sustainability, can provide meaningful insights. These technologies can, through timely data collection, monitoring and analysis, support efficiency, robustness, and sustainability of FSCs (Abbate et al., 2023).

I4 technologies may enable monitoring food products from harvest to retail, helping detect food spoilage and highlight operational efficiencies in the upstream part of the supply chain (Despoudi, 2021). At the downstream stages, digital technologies implemented in retail and food consumption can be deployed to avoid wastage, allowing improved food stock management, dynamic pricing, redistribution, and donations of food surpluses (Michelini et al., 2018).

This literature review explores the intersection of CE and technology in food systems, examining the role of innovative technologies in fostering a circular approach to food production, consumption, and waste management. Therefore, the aim of this study is threefold: 1) Review existing literature on the use of I4 technologies in relation to CE in FSC. 2) Identify potential I4 technologies that could allow for more circular FSCs. 3)Critically analyse the challenges of I4 technologies for addressing circular FSC by identifying factors impeding optimum utilisation, and evaluating solutions for a CE.

In food systems, the CE goes beyond the traditional industrial 10R framework to include biological cycles. Instead, as the agri-food systems are biological in nature rather than technical, CE emphasises prevention and reduction of food waste, redistribution of food (where possible), valorisation of by-products, nutrient and energy recovery for continual use in agro systems (Morseletto, 2020). Within this framework, I4 technologies serve as critical digital enablers, making these cycles measurable, traceable, and optimisable. For example, IoT sensors monitor freshness and spoilage in real-time to reduce waste; blockchain ensures transparency in surplus food redistribution networks; AI and BDA improve forecasting and by-product valorisation; robotics enhances precision and decreases post-harvest losses; and smart-factory systems automate recycling and energy recovery. By explicitly connecting each technology to specific CE principles, this study positions I4.0 not merely as a general sustainability tool but as a structural driver of circularity in FSC.

While prior reviews have examined the role of I4 technologies in FSCs or sustainability more broadly, this study makes several distinct contributions to the CE literature. First, it provides a comparative analysis of six core I4 technologies (IoT, AI, blockchain, BDA, smart factory systems, and robotics) within a unified CE framework, focusing on FSC, rather than focusing on a single technology or isolated use cases. Second, the study explicitly links each technology to specific CE strategies, including food waste reduction, food redistribution, by-product valorisation, and nutrient recovery, thereby moving beyond general efficiency or digitalisation narratives (Pakseresht et al., 2023). Third, by analysing real-world digital platforms and implementation examples, the review bridges the gap between conceptual research and operational practice, particularly in food systems. Finally, the study reframes I4 not merely as a technological upgrade but as a structural enabler of circularity, offering a holistic perspective through policy recommendations on how digital technologies collectively support the transition from linear to circular FSC. By synthesising existing knowledge and identifying gaps in research and the practical implications of deploying these technologies, this review can guide future studies, inform industry practices, and support policy development aimed at achieving a more sustainable and resilient FSC. Together, these contributions distinguish this review from prior studies and provide a more integrative and practice-oriented understanding of I4–enabled circular FSC.

2. Background: I4 in Circular FSC

The CE framework advocates for a regenerative approach to resource management, emphasising strategies such as the 10Rs, encompassing reduction, redistribution, repurposing, reuse, and recycling (Alonso-Muñoz et al., 2022). In the food sector, CE initiatives address the particularities of biological cycles and thus focus on: prevention and reduction of food waste, redistribution of food (where possible), valorisation of by-products, and nutrient and energy recovery (Pal et al., 2024). Prevention and reduction strategies of agri-food waste include enhancing production and processing methods to prevent losses, reducing spoilage during transportation, and aligning consumption with actual needs. Redistribution of surplus agricultural products and food can be achieved within industries and among consumers (Papargyropoulou et al., 2014). Valorisation is accomplished through advanced biochemical processes, which transform bio waste into valuable chemical products required in industries such as the pharma or cosmetics (Principato et al., 2015). Transforming organic waste into compost recovers nutrients existing in waste, while the caloric energy of agri-food waste can be captured and transformed into other types of energy outputs (Scherhaufer et al., 2018; Salim et al., 2021). Implementing CE principles in food systems not only addresses environmental concerns but also offers economic and social benefits by creating sustainable and efficient FSCs (Alonso-Muñoz et al., 2022).

I4 technologies, structured on several technological pillars: IoT, AI, BDA, Blockchain, Smart Factories and Robotics have made promises to radically revolutionise the food industry and claim to offer several solutions to prevent food wastage, improve food quality and safety by using analytics, sensors, automation, and traceability solutions (Annosi et al., 2021). These I4 technologies can play a key role in addressing the challenges faced at the production and distribution stages.

BDA empowered by sensor technologies can optimise farm production, reduce losses, and enhance resource efficiency. It can also increase identification of patterns in consumer behaviour, market trends, and potential risks, providing valuable insights for innovation and decision-making in food production and distribution (Ahmadzadeh et al., 2023; Rajesh et al.,2022) IoT sensors enable real-time monitoring of chemical, physical, and biological parameters throughout the supply chain, offering immediate feedback and alerts to maintain food quality and safety (Da Costa et al., 2023). Blockchain technology offers an immutable and decentralised ledger system that improves traceability and accountability, thereby reducing the likelihood of food spoilage by enabling rapid identification and removal of contaminated products.

Technology-driven initiatives are increasingly targeting consumers to raise awareness about food waste and encourage behavioural change. Mobile applications, augmented reality, and social media platforms are utilised to educate consumers on proper storage, portion control, and the utilisation of leftovers, fostering more sustainable food consumption patterns. Mobile applications like "Too Good To Go" connect users with local businesses offering surplus food at discounted prices, making surplus food accessible and affordable while reducing waste. Studies indicate that such apps can positively influence consumer behaviour by promoting sustainable consumption practices (Balinska et al., 2024). Social media platforms play a significant role in shaping consumer attitudes toward food waste. Engaging campaigns and community-driven content on social media platforms like Instagram and Facebook have been shown to raise awareness and promote food waste reduction behaviours among users (Aschemann-Witzel et al., 2022). Augmented reality (AR) technologies have also been explored as tools to enhance consumer awareness of food waste. Research suggests that AR can effectively educate consumers about food waste patterns and encourage more mindful consumption habits (Hurst et al., 2022).

While digital technologies may contribute to food waste by serving as platforms for overproduction and consumption, they may also provide valuable solutions for circular FSC. Digital technologies may support sustainable product innovation, minimising losses, and waste across the FSC, and encouraging stakeholders to implement more resource-efficient practices, thereby fostering a CE within the food sector. However, the extent to which digital technologies effectively support CE principles and contribute to waste reduction remains relatively unknown. This review aims to address this gap by methodologically analysing how these technologies have been applied, as reflected in existing academic literature.

This study is grounded in core CE principles related to biological cycles, notably, the prevention and reduction of food waste, redistribution of food, valorisation of by-products and nutrient and energy recovery. We frame our analysis around how I4 technologies bolster these principles. By explicitly adopting the CE lens, we demonstrate how each I4 solution contributes to keeping resources in circulation and designing out waste.

3. Methodology

This study adopts a systematic literature review approach to evaluate the role of I4 technologies in enabling CE practices within FSCs. The review follows a structured search, screening, and selection process informed by PRISMA principles to enhance transparency and replicability. The full selection process is illustrated in the PRISMA-style flow diagram presented in Figure 1.

3.1. Database search and identification of studies

For the literature review, peer-reviewed publications were retrieved from three major academic databases: *Web of Science, Scopus, and ScienceDirect* (hereinafter "academic database search"). To capture emerging technological applications and real-world digital platforms not fully indexed in academic databases, Google Scholar was used to identify grey literature and industry case material.

A common search string was applied across databases: ("Industry 4.0" OR "I4") AND ("circular economy") AND ("food supply chain" OR blockchain OR "artificial intelligence" OR "big data analytics" OR "smart factory" OR "Internet of Things" OR robotics).

The academic database search was limited to publications from 2013–2024, reflecting the period during which I4 technologies began to gain sustained scholarly attention beyond their initial engineering applications and became increasingly linked to supply chain sustainability research (Ahmi et al., 2019). The academic database search yielded 127 records.

3.2. Screening and eligibility assessment, including inclusion and exclusion criteria

Following identification, metadata were exported to Excel and screened using predefined inclusion and exclusion criteria. Studies were included if they were: (i) peer-reviewed journal articles or conference papers; (ii) published in English between 2013 and 2024; (iii) examined one or more core I4 technologies (IoT, AI, blockchain, BDA, smart factory systems, or robotics); (iv) relevant to FSC and potential contributions to CE strategies.

Studies were excluded if they: (i) were not peer-reviewed academic sources (except for selected case study documentation); (ii) did not address the FSC context; (iii) focused solely on technological performance without implications for resource efficiency or waste reduction.

Duplicate records were removed using Mendeley reference-management software. After screening for language, date, and duplication filters were applied, we screened for irrelevant articles based on title and abstract. 93 potentially relevant studies remained, which underwent a full-text assessment. The detailed full-text appraisal was conducted to evaluate methodological rigour, thematic relevance, and contribution to CE-related practices. At this stage, CE considerations were operationalised through content analysis. Articles were retained only if they demonstrated a clear contribution to at least one CE strategy relevant to biological resource loops, including: (i) prevention or reduction of food loss and waste, (ii) redistribution of food, (iii) recovery of nutrients or energy, or (iv) valorisation or secondary use pathways. This approach ensured that the selected studies captured a broad range of CE strategies, associated with CE of biological loops, even where explicit CE terminology was not used by the original authors. Following this detailed appraisal, 73 studies were selected for inclusion in the final systematic review.

In parallel, 13 empirical case studies (Table 5) were identified through grey sources, industry reports, and publicly available documentation (such as websites). Case studies were included only if they: (1) applied at least one I4 technology in practice; (2) operated within the FSC; (3) demonstrated observable contributions to circular practices such as waste reduction, redistribution, or improved utilisation of unavoidable food waste. Purely conceptual cases, lacked a clear digital component, or did not demonstrate a link to CE outcomes were excluded.

3.3. Coding and analytical approach

73 selected studies were coded according to publication characteristics, technological focus, and the primary challenges associated with implementing I4 solutions in circular FSC contexts. Coding was conducted manually using Microsoft Excel to enable cross-comparison across studies. To ensure consistency, coding decisions were guided by predefined inclusion rules, and ambiguous cases were discussed among the authors until consensus was reached.

In addition to the journal name and publication year, we code for the academic scope of the journals included in the review. Journals were grouped in one of the following four categories: 1) Environment and Sustainability; 2) Agri and food; 3) Technology and Engineering; 4) Economic and Management, as reported in Figure 2.

Our coding and case selection focus on six core I4.0 technologies: IoT, AI, BDA, Blockchain, Smart Factory, and Robotics, due to their direct and documented impact on FSC performance and alignment with CE principles. These technologies were prioritised over others (e.g., augmented reality (AR), 3D printing, or Digital Twins) for three primary reasons. Firstly, the selected technologies are widely cited in both academic and industry literature as key enablers of reduced spoilage, real-time monitoring, dynamic inventory control, and predictive resource management, which are critical objectives in CE-aligned food systems. Secondly, these six technologies have seen practical deployment in the food industry, with robust implementation data available from multinational corporations (e.g., Nestlé, Walmart) and start-ups alike. The availability of real-world data allows for meaningful, evidence-backed evaluation and comparison. Thirdly, in contrast to more specialised or emerging tools, the selected technologies support integration across the entire FSC, spanning from agricultural monitoring (IoT, AI) and processing (Robotics, Smart Factory) to distribution (Blockchain) and strategic analytics (BDA). This cross-functional applicability is essential in a circular model aiming for holistic transformation.

While other advanced technologies, such as Digital Twins, Geographic Information Systems (GIS), Remote Sensing, and AR, are acknowledged within the literature, their mention in this paper remains brief. The aim is to analyse technologies with direct, high-frequency use cases in FSC CE strategies. Digital twins, for instance, are powerful simulation tools but are often more prevalent in industrial engineering contexts than in food logistics or perishability management. Technologies like GIS and remote sensing are valuable for land use and environmental mapping; they are not yet as commonly integrated into end-to-end FSC digital platforms focused on waste reduction, redistribution, or traceability.

The challenges posed by the I4 technologies were initially coded under one of the following: Security & Privacy; Platform Management; Technological Architecture; Managerial; Sustainability; Education and Awareness; Government Policies; Standardisation; IoT-based Infrastructure; and Financial, as shown in Table 2. Some of the challenges were common to several technologies, while some were unique. To make the analysis more coherent, similar challenges were grouped under common factors (technical, social, economic, institutional, organisational, and infrastructural), summarised in Table 2.

Absolute frequency counts were subsequently converted into relative frequency weights to indicate the prominence of different technologies and implementation challenges within the literature. These weights reflect patterns of scholarly attention and research emphasis rather than direct measures of technological effectiveness in achieving CE outcomes.

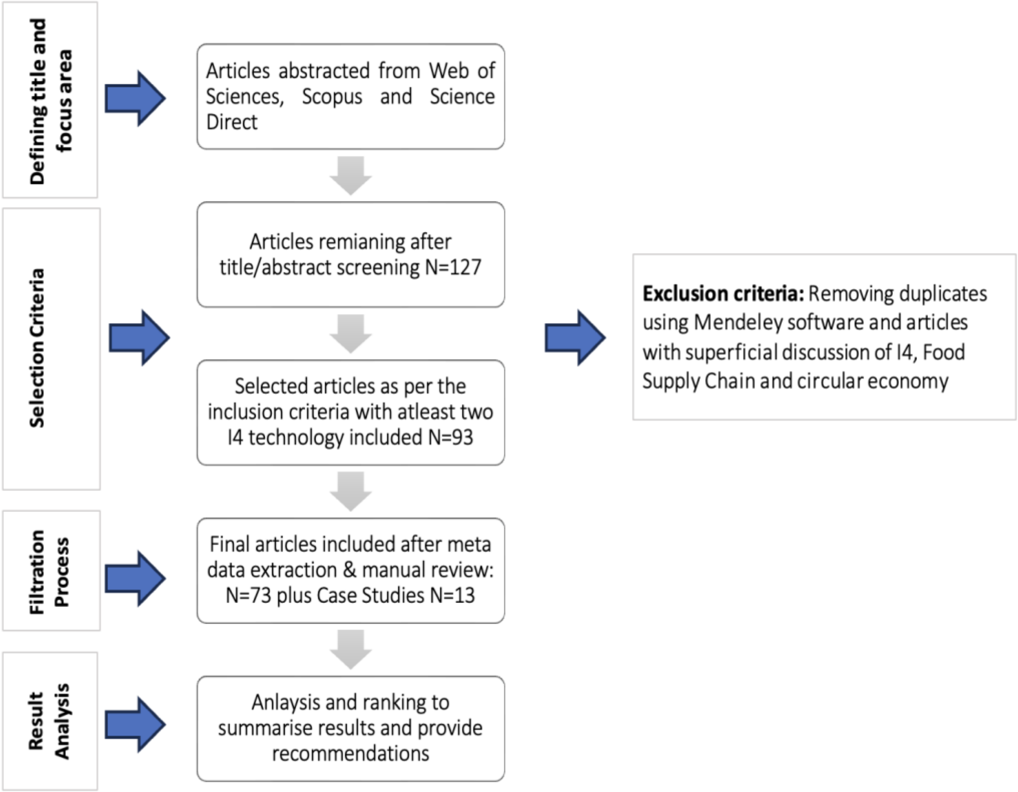

Figure 1. Flow Diagram-The diagram above illustrates the selection criteria in the PRISMA flow diagram style, the filtration process, including the inclusion and exclusion process and result analysis. *(Source: Author's work)*

4. Analysis & Results

Figure 2 is a quadrant diagram that categorises the source journals based on their disciplinary focus, highlighting the richness of disciplinary interest in the topic and the different approaches used in the articles. The bubble sizes reflect the number of publications within each category, illustrating the dominance of research relating to sustainability and the environment, as well as research more driven by management and economics, with a technology focus.

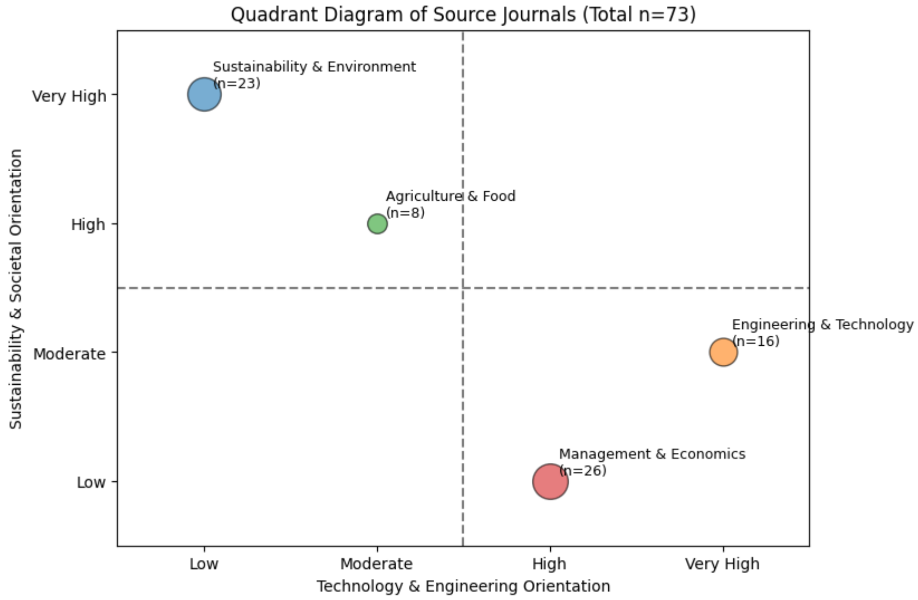

Figure 2. Quadrant Diagram of Source Journals - Selected 73 journals have been grouped in one of the following four categories: Environment and Sustainability; Agriculture and food; Technology and Engineering; & Economic and Management in the figure below. *(Source: Author's work)*

A trend analysis of the number of publications in each year within the period of our study can be seen in Figure 3. Most of the relevant studies on FSC, I4 and CE were published from 2020 onwards, and hence, there is limited research or literature available on this field of study. Although I4 technologies have existed for over a decade, their impact on the FSC began to be explored more recently, as shown. Our analysis of cases presented in the papers included in the scope of the review shows that these tools have been used more frequently in the past five years, and thus, there is a significant increase in exploring this area further, confirming the scientific interest in applying I4 technologies to the FSC.

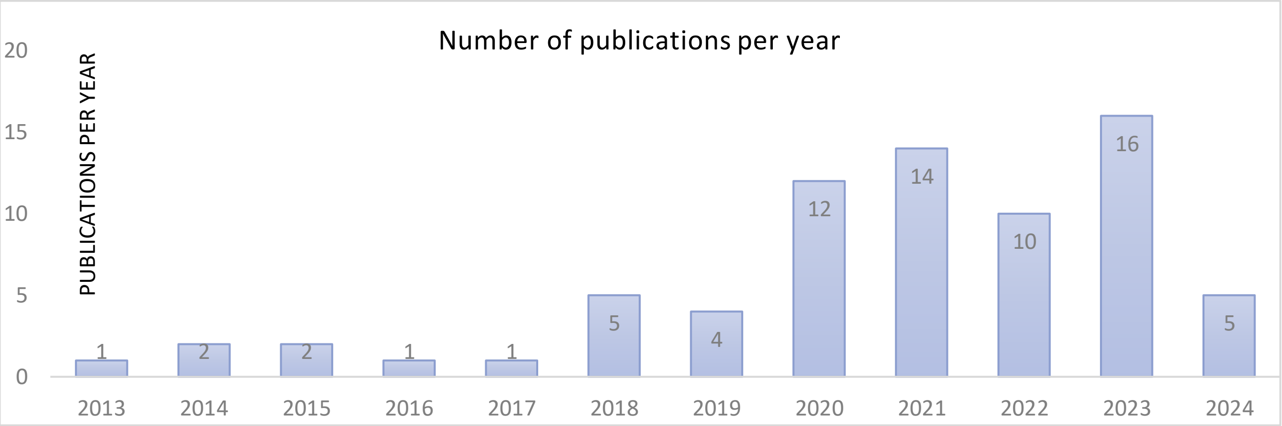

Figure 3. Number of publications per year studying the impact of I4 technologies within FSC for CE - A trend analysis was conducted within the period of our study of the number of publications in each year, and as can be seen below, most of the relevant studies were published from 2020 onwards, and hence, there is limited research or literature available on this field of study. *(Source: Author's work)*

Figure 4 below indicates the frequency of each technology analysed in our selected articles. IoT is analysed in 36 different articles in our selected papers, followed by AI in 27 papers, Blockchain in 25 papers, BDA in 21 papers, Smart Factory in 16 papers and Robotics in 8 papers. The review suggests that both IoT and AI are most prevalent and hence potentially most influential in this field, whereas smart factories and robotics seem to be less utilised, as per the review.

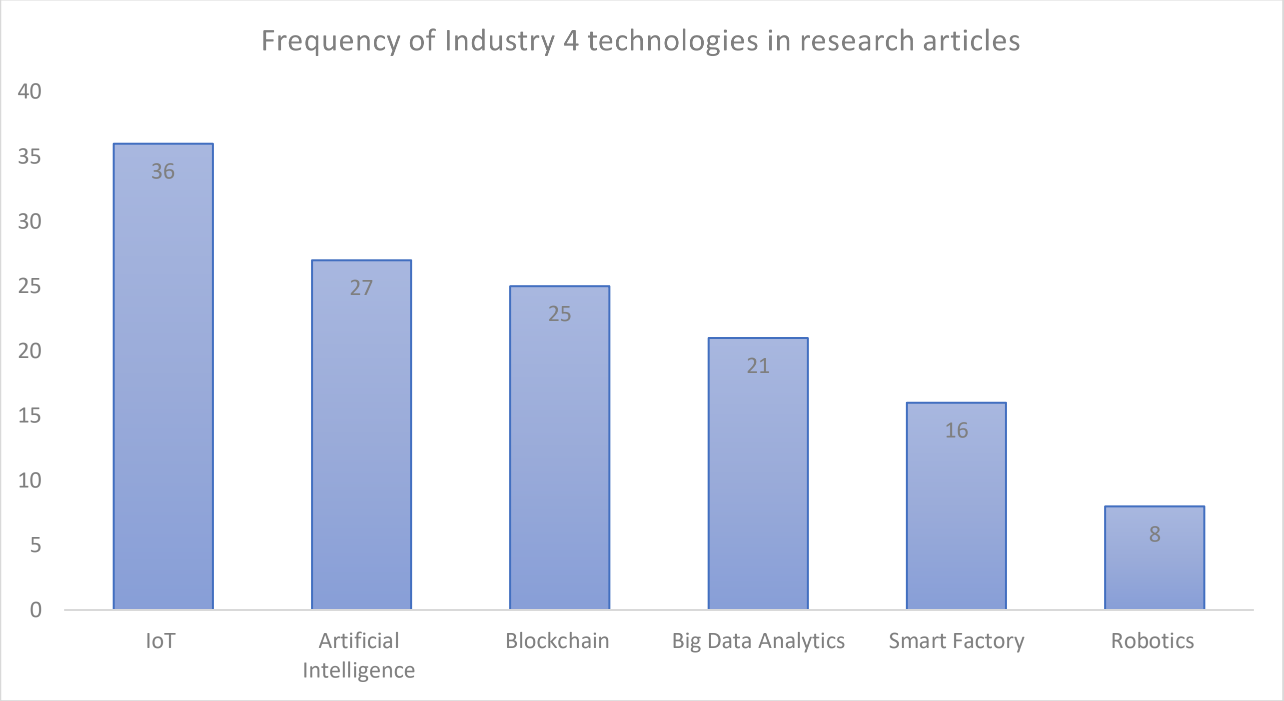

Figure 4. Frequency of Industry 4 technologies in research articles - The diagram below indicates the frequency of each technology identified in our selected studies, indicating that IoT and AI were the most prominently referenced technologies. *(Source: Author's work)*

Our results indicate that out of all the above-mentioned I4 technologies, IoT is the most dominant technology when it comes to the FSC to prevent waste loss in the CE. The second most prevalent tech for the FSC to prevent food wastage is AI, and the third most helpful is blockchain technology. Further, frequency-based normalisation was used to synthesise the results by converting raw occurrence counts into relative values. Specifically, the number of studies addressing each technology was divided by the total number of reviewed journal studies, enabling comparison of the relative prominence of technologies across the literature. These normalised values reflect patterns of research emphasis rather than empirical measures of CE performance. For example, if a particular technology related to the IoT appeared in 36 out of 73 reviewed articles, its normalised frequency was calculated as 36/73 = 0.49, as shown in Table 1. These values allow comparison of the relative attention given to different technologies across the literature.

Table 1. Frequency-based weightage of technologies in literature review - This table shows the frequency-based normalised distribution of I4 technologies across the reviewed studies, highlighting IoT, AI, and blockchain as the most prominently addressed solutions for reducing food waste in the FSC. *(Source: Author's work)*

I4 Technology	Weights
Internet of Things	0.49
Artificial Intelligence	0.37
Blockchain	0.34
Big Data Analytics	0.29
Smart Factory	0.22
Robotics	0.11

The papers were then qualitatively analysed to identify the challenges addressed with regard to implementing and achieving CE using I4 technologies, as in Table 2. We have further analysed each technology to understand its limitations by different themes and provided ranks as in Table 3 using the same frequency-based normalisation as above, which determined the importance of each factor in optimum utilisation within FSC.

Table 2. Challenges in implementing I4 technologies in FSC for CE - The table below groups the identified challenges into common factors (technical, organisational, social, institutional, infrastructural & Economic and their frequencies were recorded. *(Source: Author's work)*

Factors	Challenges	Number of Observations	Total
Technical	Security & Privacy	5	
	Platform Management	9	
	Technological Architecture	19	33
Organisational	Managerial	12	12
Social	Sustainability	25	
	Education & Awareness	27	52
Institutional Infrastructural	Government Policies	7	
	Standardization	7	14
	IoT-based infrastructure	10	10
Economic	Financial	20	20

Table 3. Frequency-based weightage of factors and their rankings - Each factor was given a rank as shown in this table using the same frequency-based normalisation as above, which determined the importance of each factor in optimum utilisation within FSC. *(Source: Author's work)*

Factors	Weights	Rank
Social	0.37	1
Technical	0.23	2
Economic	0.14	3
Institutional	0.10	4
Organisational	0.09	5
Infrastructural	0.07	6

Further analysis was conducted, and weights were determined to rank the factors that have a major impact on the successful implementation of I4 technologies. The analysis provides insight into which technology (Table 1) and which factors (Table 3) are more prevalent in the literature, potentially indicating their contribution to reducing food wastage and CE. Social factor ranks on top, which means that better utilisation of I4 in reducing food wastage can be achieved by addressing sustainability, education & awareness issues. Technical and economic challenges are the second and third largest barriers, respectively, in achieving the complete benefits of I4 in the FSC CE. Based on the insights from these findings, we develop policy recommendations, later in the paper. The purpose of this weighting process is to identify research emphasis and knowledge concentration within the existing literature, thereby highlighting areas of strong scholarly attention as well as potential gaps.

5. Role of IoT in FSC

Technologies such as IoT and other similar ones can bring about radical changes to the FSC. IoT technology is effective when it comes to food safety and security, as it allows the identification and traceability of products from farm to table (Akyazi et al., 2020). The connectivity established using IoT allows for better FSC coordination as the material, processes, and all the conditions can be tracked and traced using IoT sensors. This allows for efficient ways to share information and take critical actions, thus contributing to food safety (Annosi et al., 2021).

IoT plays a critical role in improving visibility and control across FSC through real-time monitoring of temperature, humidity, and storage conditions. These functions directly support CE strategies aimed at waste prevention and resource flow narrowing, as they enable early detection of spoilage risks, reduce quality degradation, and extend product shelf life. By preventing avoidable losses at the production, storage, and distribution stages, IoT technologies contribute to reducing the overall volume of food entering waste streams.

Furthermore, IoT-generated data supports better decision-making for surplus management and redistribution, as real-time inventory and condition monitoring allow actors to identify products suitable for alternative markets or donation before quality deterioration occurs. In this way, IoT functions not only enhance operational efficiency but also enable preventive and recovery-oriented circular strategies, strengthening the alignment between digitalisation and circular food system objectives.

As per the European Commission, IoT-based systems can play a pivotal role in several stages of the FSC, including production, storage, processing, transportation, and distribution by providing solutions for food safety (Pang et al., 2015). IoT-based systems have been utilised in rescheduling and re-calling within the food industry and provide useful insights for taking appropriate actions that prevent food wastage, creating a CE (Misra et al., 2020).

IoT is beneficial in agriculture for monitoring the conditions, establishing water and nutrient requirements of the crop, storage, and handling, and treating pests with chemicals in a controlled environment. IoT-based technologies provide opportunities in plant-based production through monitoring the growth of crops, optimal use of fertilisers and pesticides, and detecting pests. IoT can also evaluate the reasoning behind plant diseases and noxious weeds (Senturk et al., 2023).

Integrating IoT-based technologies in the FSC reduces the risk of contamination and spoilage, preventing concerns about health and economic losses (Misra et al., 2020). A large amount of data created using sensors is recorded into the databases or cloud platforms, which can then be processed using IoT devices for determining outbreaks early in the FSC.

Along with IoT, other technologies such as Geographic Information System (GIS) and Global Positioning System (GPS) are beneficial when it comes to managing and tracking the location of waste disposal vehicles (Chauhan et al., 2021). To save costs, waste disposal processes are often violated where companies dump their waste at illegal dumping grounds, including rivers and restricted sites. A GPS tracking system is helpful in such cases where such illicit activities can be tracked and avoided for managing waste via tracking systems embedded in the vehicles, thus contributing towards proper treatment and disposal of food waste within CE.

IoT becomes more relevant when it comes to I4 technologies such as blockchain, BDA and sensor devices, as these technologies are often combined to achieve desired results in the agriculture and FSC (L'heureux et al., 2017). Several tools and technologies are being deployed in the food industry, including automation, AI image processing, robotics, 3D printers, nanotechnology, and machine learning, etc. Most of these technologies are used in conjunction with IoT-based systems.

A study introduced an IoT-based digital monitoring system for managing food waste (FW). Integrating hardware and software elements, this system is essential in collecting and analysing FW data to extract valuable insights. In a practical application at a ready meal production facility near London, UK, this system significantly reduced waste levels, from 4.7% in January 2017 to 1.92% by September 2017. It efficiently pinpointed waste causes like quality issues, equipment failures, and spoilage/handling. The software provided real-time visualisations, alerts, and comprehensive FW analysis, assisting management decision-making. While the system currently requires human verification of FW details, leading to potential loss of accuracy, the study suggests that incorporating advanced image processing technologies could overcome this limitation, enhancing the system's capability to accurately record complex FW compositions. (Jagtap and Rahimifard, 2019).

Several platforms are striving to reduce food wastage and food loss for a CE in the FSC. One such platform monitors the quality of food along the entire product journey using digital twin technology (TCS, 2024). The system assesses food freshness using sensors that are installed at every stage of the supply chain. The data collected is used in the real-world supply chain digital twin model for stimulating different environmental conditions, such as humidity, temperature, air quality, etc. For example, the platform can predict the ripening duration of fruits such as mango, papaya, banana, etc., and predict the shelf-life of potatoes for different products, including chips, fries, or potato starch.

BioTrak is another such emerging platform that integrates blockchain with IoT sensors to create real-time traceability systems for cold chain logistics. By ensuring continuous temperature monitoring and providing immutable digital records, BioTrak minimises spoilage risks and enhances consumer trust through verifiable food histories (Spitalleri et al., 2023).

IoT is useful in detecting and removing deteriorated food items that are non-consumable and can be converted into secondary products through an effective process, such as food collection centres near the markets where consumers can easily return expired products (Waqas & Yuncheol, 2024).

IoT-enabled cold chain monitoring reduces food spoilage by providing real-time data on temperature and humidity deviations, which allows suppliers to act pre-emptively. This supports CE goals by reducing avoidable waste and enhancing product longevity.

6. Blockchain in FSC

One of the major issues for CE within the FSC is the lack of transparency and traceability. It is crucial to collect, store and process the data obtained from the FSC to provide the required visibility for decision-making. Databases that are traditionally used are either deployed on a single computer or a data centre that uses client-server architecture. But these databases are controlled by a centralised authority that controls access to the data. Such data management solutions are not ideal in situations where the data is required to be distributed, transparent and tamper-resistant (Truică et al., 2013).

In the CE, several stakeholders are involved within the supply chain, which requires frequent and real-time interaction for decision-making. Distributed access to data is required for implementing a CE, and blockchain technology presents a great opportunity for the FSC with its distributed, transparent, and resistant-proof nature. Blockchain comprises blocks, with each block recording the data, including a pointer to the previous block, forming a chain of blocks. Data is recorded on a new block that is added to the end of the chain, and any modification in the data recorded can only be made by changing data in all the previous blocks, making it practically difficult to tamper with the data.

Once the data is validated and stored on the blockchain, it is shared with other peers through a peer-to-peer network in different locations at the same time. This functionality is useful in the CE where access to information across stakeholders is required in real-time for preventing any breakages within the supply chain.

Traceability forms one of the most important functionalities of blockchain (Rogerson and Parry, 2020). Blockchain-based traceability applications are being deployed in the FSC. For example, a distributed secure architecture within dairy food traceability (Casino et al., 2021). The model is built on a private blockchain platform and utilises smart contract functionality, which resulted in traceability cost savings. Another example is a traceable blockchain-based system within the fruits and vegetables supply chain for storing and querying product information (Yang et al., 2021). This system resulted in improved security of private information and query efficiency, increasing the authenticity of data within the fruit and vegetable supply chain, and allowing for better traceability that could potentially reduce wastage. Another proposed model is a blockchain-based monitoring system integrated with IoT for tracking frozen aquatic products. This model proposes to solve the inefficiencies of conventional tracking systems and logistics within the aquatic FSC that are built on centralised data management systems with risks of data tampering and delayed decision-making (Zhang, D., 2020).

Blockchain also enabled farmers to track crucial information on crop yields, soil conditions, and pest infestation, allowing them to make informed decisions to optimise crop production (Awan et al., 2021). Another model based on blockchain technology proposed a traceability model where consumers can trace the product origin and whether it is made from fresh or recycled resources (Casado-Vara et al., 2018).

IBM Food Trust uses blockchain technology combined with smart contracts to create end-to-end traceability across multinational FSC. Retailers such as Walmart have reported a significant reduction in traceability time from seven days to just 2.2 seconds after adopting the IBM platform, highlighting its effectiveness in reducing waste and improving supply chain responsiveness (WEF, 2019).

Similarly, FoodLogiQ offers cloud-based solutions combined with blockchain to manage supply chain compliance, food recalls, and transparency initiatives, reinforcing food safety and reducing systemic inefficiencies (FoodLogiQ, 2023). Additional platforms like TE-FOOD provide farm-to-fork livestock and produce traceability through blockchain and QR code technologies, particularly targeting emerging economies where food safety infrastructure is underdeveloped (TE-FOOD, 2021).

Integrating blockchain with emerging sensing technologies is potentially beneficial in monitoring the biological conditions of various food products (Altay et al., 2022). A blockchain-based multi-sensor monitoring system examined the collection of quality parameters and improved the transparency of shellfish during storage, incorporating Hazard Analysis and Critical Control Points (HACCP). The results indicated improved quality of frozen shellfish as the system provides a reliable real-time monitoring of dynamic indicators, also reducing losses (Feng et al., 2020). Overall, multiple cases and developments provide evidence that blockchain technology could tackle food safety traceability, reducing food waste by detecting unsuitable food for consumption across the supply chain in real time.

Standards like the EU's General Food Law and the U.S. Food Safety Modernisation Act (FSMA) focus on traceability within specific supply chain stages. However, these measures lack a global standard for digital data tracking and are more applicable at the regional level. Blockchain has been applied experimentally at the tail end of the supply chain, integrating with a real-time food management app called ‘Smart Nosh Waste,’ which is designed within the framework of smart cities (Dey et al., 2022). The proposed app's framework offers a versatile solution to reduce food waste while addressing global differences in standardisation. Researchers utilised app data in their experiment on 'potato' consumption, documenting 134,996 instances globally over a year. Findings reveal the framework used by the app reduces food waste by an extra 9.46%.

7. AI in FSC

Despite advancements, undernourishment remains a pressing issue, especially in densely populated nations like India and China. Economic growth, demographic shifts, and increased greenhouse gas emissions complicate the situation. The food industry, traditionally slow in adopting innovations, is now witnessing a paradigm shift with the growth of the I4 technologies like AI. AI holds promise in optimising FSC, reducing waste, and improving production efficiency. By leveraging AI for better forecasting, efficient resource utilisation, and minimising environmental impact, the food industry can significantly contribute to addressing the looming food crisis. AI-driven techniques and machinery in agriculture and the food industry have transformed crop farming, cultivation, production, and processing methods. (Kakani et al., 2020).

Integrating AI and machine learning (ML) into supply chain management improves food product traceability, addressing inefficiencies and reducing food waste. AI and ML-enabled robots allow selective and timely crop harvesting by accurately detecting ripeness indicators during harvesting, thereby minimising waste and improving efficiency. This integration also helps farmers plan planting and harvesting schedules, optimise crop management, identify pests and diseases early, and minimise crop losses. Computer vision supports CE goals in the FSC by enabling efficient livestock monitoring, disease detection, and quality control (Mota et al., 2019).

In a study, a fault detection method was developed for smart agricultural equipment using a Recurrent Neural Network (RNN) model. An RNN is a type of AI, specifically in machine learning, designed to recognise patterns in data sequences, such as time series data, making them suitable for applications like fault detection in smart farming equipment. This model was trained using hourly data gathered from a strawberry farm. The application of this technology led to more autonomous and efficient farm operations, reduced equipment damage, and improved integration with insurance systems (Choe and Lee, 2023).

Furthermore, to combat food wastage on the retail end, Afresh, a US-based AI platform, showed the impactful integration of AI technologies. This AI system helps grocers make data-driven decisions, improve operational efficiency, and minimise food waste. It provides real-time insights into inventory management, product shelf life, and customer demand (Afresh Technologies, 2023)· Afresh's AI has led to notable improvements: a 3% increase in sales, 80% fewer stockouts, 25% less product waste, and a 7% faster inventory turnover rate. This highlights the significant role of AI in promoting sustainable and efficient food distribution.

Similarly, Nestlé employs AI-driven predictive analytics to optimise inventory management and transportation routes, thereby reducing excess stock, fuel consumption, and overall environmental impact. Additionally, the company leverages AI in product development to rapidly analyse consumer preferences and adjust formulations or packaging, accordingly, shortening development cycles and minimising resource waste. A particularly forward-looking initiative involves AI-supported personalised nutrition, where algorithms analyse individual dietary data to deliver tailored nutritional recommendations—an approach aligned with both consumer well-being and CE goals by encouraging efficient resource use and minimising overconsumption.

These initiatives support the broader objectives of the CE by fostering data-driven decision-making, lowering emissions, and aligning production more closely with actual demand (DigitalDefynd, 2025).

Fresho has developed an AI-powered platform that automates order processing, converting various order formats, such as emails, PDFs, texts, and voicemails, into structured data. This automation reduces manual entry errors and streamlines operations for fresh food wholesalers. By providing real-time pricing and availability information, Fresho enables suppliers to make informed purchasing decisions, aligning inventory with actual demand. This approach minimises overordering and food waste, addressing the significant issue of fresh food wastage, which accounts for up to 30-40% globally (Fresho, 2024). Fresho's initiatives support CE principles by reducing excess inventory, lowering emissions through optimised logistics, and aligning production more closely with demand.

Another research study proposes combining intelligent waste bins using sophisticated object detection. These smart bins analyse disposed waste, providing insights to enhance the efficiency of raw material utilisation in food preparation. They also integrate inventory prediction and forecasting techniques (Agarwal et al., 2020). In the Netherlands, Orbisk caters to various restaurant operators with such smart bins. The device seamlessly integrates into kitchens and offers valuable insights for optimised inventory purchasing decisions. The bin automatically identifies the type and quantity of discarded food, displaying data on a clear dashboard for future food waste prevention (Orbisk, 2024)· Users only need a brief pause before discarding food, and the captured data is sent to the cloud for AI processing. The company aims to improve user experience and is developing a predictive sales tool based on waste analysis (Orange, 2023)·

Savvie, an application from Norway, uses AI to help cafes and bakeries increase their revenues and significantly reduce waste. Savvie features AI-driven sales forecasts, automated ordering, and strategies for waste reduction. These strategies include establishing waste targets, monitoring trends, tracking unsold products in real-time, and analysing product trends. The application has been reported to help reduce waste by up to 75% (Savvie, 2024).

In absolute terms, most food waste is produced at the household stage of the FSC. Simeone et al. (2022) suggested a recipe suggestion tool that aims to connect food suppliers and consumers for smarter food planning, purchasing, and consumption. This approach uses data-driven tools to suggest recipes tailored to users' preferences, available food items at home, their expiration dates, and minimum packaging sizes.

Furthermore, the Nosh app, using AI, understands users' consumption and waste patterns and provides weekly analytics to help reduce waste and optimise grocery spending. The app allows users to scan barcodes or manually input data to maintain a detailed inventory of their pantry and fridge. Consequently, users can access online recipes designed to efficiently use their existing stock, thus minimising waste (Silberling, 2023).

8. Robotics in FSC

Robotics within the I4 framework has revolutionised food manufacturing, covering all stages from soil preparation to retail operations. These intelligent robots are cognitively and environmentally conscious, enabling them to make collaborative decisions and adapt to various tasks, such as changing robotic hands for different processes. They are important in improving food quality, process performance, production rates, and supply chain resilience. Additionally, their contribution to minimising food loss and wastage, improving hygiene, and ensuring better traceability is significant. Equipped with machine learning and image analytics for quality assurance, these robots are operable remotely via human-machine interfaces (HMIs) with augmented reality for precision monitoring. Key drivers for adopting robotics in food manufacturing include cloud manufacturing, IoT, virtual and augmented reality, and autonomous software, all contributing to the minimisation of waste of food and raw materials (Barasa and Yonah, 2023).

Understanding the importance of quality monitoring during storage is crucial, especially for harvested fresh produce, which remains biologically active. This activity leads to respiration and heat production in the produce. Higher temperatures or stress can accelerate respiration, speeding up deterioration and ripening. Without proper control, this can result in significant wastage of fresh produce within days or weeks. Storage strategies include temperature reduction, oxygen lowering, carbon dioxide increase, and stress avoidance to manage this. In this context, a study focuses on the role of robotics in the post-harvest process, particularly in maintaining and assessing produce quality during storage. Automated Mobile Robots (AMRs) are beneficial in these scenarios due to their high payload capacity, autonomous movement, and sensing abilities. They enable real-time monitoring and efficient stock management, integrating quality and climate data to improve warehouse operations and detect deteriorating products early (Chauhan et al., 2022).

The use of computer vision along with robotics has been beneficial in providing innovative solutions in farming through data inspection and land surveys. Drones and aerial systems play an integral part in crop management as they have multi-spectral sensors embedded in them that help in decision-making for the inspection of water requirements, soil fertility, etc. Until 2010, farmers utilised satellite images for extracting images, which would take over two weeks, further prolonging the time in case of bad weather. Computer vision reduces this time significantly, as the multi-sensor imaging system embedded in the drones easily allows the identification of infected plants through infrared sensory imaging. It also allows for managing water irrigation and reducing water wastage.

A study explored the use of robotics to reduce food waste at the household level, where waste often results from unfinished meals and not checking existing food supplies before shopping. Specifically, it examined the humanoid robot Pepper, designed for human interaction with capabilities for verbal communication and interactive displays (Khan and Prasetyo, 2023). The robot was programmed and trained to recognise fruits and vegetables through image analysis, determining if items were ready to eat or needed storage. Pepper categorised items accordingly to prevent waste. For example, if a banana were ripe, Pepper would inform the user of its condition and how long it would remain fresh. If the banana was unripe, the user would be notified that it would be ready in a few days and should be stored. This research aimed to improve food quality assessment and reduce household food waste using robotic technology (Khan and Prasetyo, 2023). Another study conducted in Sweden examined how implementing Robotic Process Automation in grocery stores could streamline tracking food expiration dates, reducing food wastage (Leffler et al., 2023).

9. BDA in FSC

Leveraging BDA to reduce food wastage is a crucial development in the food industry. This has improved the efficiency of the FSC, contributing significantly to waste reduction. Ahmadzadeh et al. (2023) further explore the role of IoT and big data systems in minimising food waste, especially in supply chains, highlighting their impact on resource management efficiency.

Rajesh et al. (2022) highlight the effectiveness of BDA in refining agricultural practices, conserving resources, and reducing waste. Their study highlights the impact of BDA in improving agricultural productivity and promoting sustainable food consumption and waste management. Farmers can improve crop yields by leveraging weather and soil conditions data to meet growing food demands. The study also addresses the common yet inefficient use of fungicides in farming, noting how big data offers more refined and effective fungicide solutions, leading to healthier plant growth.

Furthermore, BDA plays a key role in optimising the supply chain, improving the efficiency of transport and delivery, and thus reducing food wastage from farm to market. Advanced analytics provided by BDA allow for accurate crop yield predictions, aiding in effective crop cultivation and harvest planning. Additionally, insights offered by BDA into soil and crop conditions support organic farming methods, improving food safety by minimising the use of chemicals (Rajesh et al., 2022). Retailers can impact upstream and downstream activities in the supply chain through their operational choices and interactions with consumers. They can affect production trends by forecasting demand, influencing consumer buying habits, and deciding what happens to unsold food items using data analytics (Beretta et al., 2013).

Monteiro et al. (2021) explore the use of Big Data in effectively managing the shelf life and pricing of fruits and vegetables. Their research proposes using cameras and odour sensors in stores to monitor the freshness of produce by capturing visual and scent characteristics. This data is then stored and analysed to predict the deterioration timeline of these items, preventing food waste.

Furthermore, Ciccullo et al. (2022) discuss the application of BDA in food waste management with the Phenix app, designed to repurpose unsold products towards the end of the supply chain. This app offers unsold items to both sellers and individuals at reduced prices, promoting ecological sustainability and cost savings. It encourages users to make environmentally conscious choices by rescuing unsold food. Additionally, the app is involved in various sustainable practices, including charitable donations, animal feed contributions, compost production, and bioenergy generation from the remaining unsold products, demonstrating a comprehensive approach to waste management.

10. Smart Factory in FSC

A smart factory is a highly digitised and connected production environment that embraces the principles of smart manufacturing. It integrates data across physical assets, operational systems, and human resources to improve manufacturing, maintenance, and inventory management. This results in an efficient, flexible, and forward-thinking manufacturing system, capable of proactive and predictive operations (Sevic and Keller, 2021).

I4 also brings advanced technologies to the industrial sector. It offers the potential for creating intelligent manufacturing platforms and advanced supply chain systems, leading to higher productivity and reduced wastage/loss by thoroughly addressing essential requirements (Ojo et al., 2018).

Big Data's application in Smart Farming significantly transforms the FSC and alters the stakeholders' roles and dynamics (Wolfert et al., 2017). In the agri-food industry, the "Smart Factory" provides a framework to tackle various food manufacturing challenges such as food safety, security, control, perishability, competitive pressures, and demand forecasting. This transformation is enabled by key elements like robots, sensors, and cyber-physical systems. These components support various activities, from operating machinery to making decisions within the agribusiness sector (Panetto et al., 2020).

Technological advancements, particularly the adoption of drones in agriculture, have revolutionised traditional farming practices. These drones, both aerial and ground-based, assist in various tasks such as assessing crop health, monitoring, planting, spraying, and field analysis. Their use, in conjunction with real-time data for strategic planning, has significantly improved agricultural practices (Javaid et al., 2022).

Platforms such as Siemens MindSphere leverage Digital Twin technology, creating virtual replicas of agricultural fields, supply chains, and processing plants to optimise operational parameters. These Digital Twins allow producers to simulate environmental conditions and supply chain disruptions before they occur, leading to resource savings such as a reported 25% reduction in irrigation water use during pilot projects (Siemens, 2022).

Furthermore, the incorporation of IoT in agriculture has combined modern technology with traditional farming methods, and when combined with other technologies such as BDA, blockchain, and AI, it leads to smart farming. This integration improves production efficiency, quality, and yield. By collecting and analysing data from various sensors, either in real-time or through databases, farmers can make swift decisions, reducing crop damage. Smart greenhouses, which automate environmental conditions like temperature and irrigation, further reduce the need for manual intervention. Additionally, farm management systems integrate data from fields, larger farming equipment, weather stations, and global markets, providing comprehensive insights for risk management and financial planning. This holistic approach to data utilisation helps reduce waste by converting the residual agricultural waste into energy and maximising agricultural output (Javaid et al., 2022).

In another study (Abideen et al., 2021), the authors analysed literature and data on agricultural farming, production, and processing, pinpointing the need for more research on integrating intelligent supply networks and digital technologies. They particularly focused on the role of AI and machine learning in improving food transportation, demand forecasting, shipping of perishable goods, and ensuring food safety and quality.

The study highlights the importance of blockchain technology for effective supply chain management and financial transactions, especially for maintaining quality, safety, and sustainability in the FSC amidst challenges like the COVID-19 pandemic. It suggests integrating IoT and big data to improve cooperative partnerships and strategies.

Abideen et al. (2021) also discuss digitalising government regulations and audits using blockchain and IoT to support the FSC. It foresees cyber-physical systems playing a key role in food processing and packaging, particularly in reducing human contact during pandemics. Blockchain and big data technologies are also proposed for environmentally and economically sustainable farming practices.

The authors recommend technological solutions at different FSC stages to address scalability challenges. The study highlights the need to reduce costs in logistics, freight, energy, fuel, manpower, and technology investments to lessen the bullwhip effect in the supply chain. Using IoT for extensive data analysis can help identify cost trends and provide predictive solutions for better decision-making. The paper underlines the importance of maintaining high-quality and safety standards for success and improving visibility and interaction within the FSC (Abaideen et al., 2021).

The introduction of programmable logic controllers (PLCs) facilitated the real-time adjustment of cutter and conveyor speeds, enhancing production efficiency. A central cloud-based dashboard, a hallmark of I4, consolidates data collection, visualisation, and machine learning predictions, aiding in decision-making. The application of virtualisation principles led to the creation of a digital twin of the factory, offering a simulated environment for monitoring, simulation, and decision support. This included three virtual monitors focusing on resource management, including consumption, production efficiency, and stock levels. The dynamic temperature regime and dashboard visualisations enabled the production team to effectively troubleshoot and refine processes. Overall, these integrated I4 elements collectively improved productivity, consistency, and decision-making in the food manufacturing sector, as detailed by Konur et al. (2023).

On the other end of the spectrum, Smart Packaging (SP) in the food industry focuses on improving food quality, safety, and traceability throughout the supply chain. A key part of SP is active packaging, which maintains high-quality food by incorporating components that either release or absorb substances to prevent spoilage. Food spoilage, which can be affected by temperature, pH, and humidity, leads to chemical and microbiological alterations that affect the taste, safety, and texture of the food. Technologies such as integrity indicators, spoilage sensors, and smart RFID tags are used to monitor changes in food properties in real time, aiding in effective spoilage prevention, as noted by Chen et al. (2020).

Another study explores smart warehousing within a smart factory setting to ensure crop quality by managing warehouse factors like temperature and humidity. This approach considers both external and internal environmental conditions, using a decision tree algorithm, a type of supervised machine learning, for temperature control decisions (Iturbe et al., 2021). Smart warehousing incorporates IoT technology to monitor storage conditions, enhancing post-harvest crop preservation. IoT sensors in the warehouse continually gather environmental data, allowing farmers to quickly react to changes. This system provides real-time temperature and humidity updates using NodeMCU and sensors, with air conditioning often used to maintain the quality of fruits and vegetables (Anoop et al., 2021).

Additionally, the study introduces a traceability system using RFID and IoT sensors. RFID technology tracks perishable food, while IoT sensors monitor temperature and humidity during storage and transportation. The study highlights the use of RFID gates to determine tag direction (inward or outward) and shipment status, employing machine learning models to identify the direction of passive RFID tags. These models consider factors like receive signal strength (RSS) and tag timestamps. Applied in the perishable FSC, this system provides real-time product information and a comprehensive temperature and humidity history, benefiting managers and customers. The integration of machine learning with RFID gates improves the identification accuracy of tagged products, enhancing the traceability system's efficiency (Alfian et al., 2020).

Furthermore, the integration of reinforcement learning, prescriptive intelligence in route optimisation (AI/ML), and data-driven simulation modelling addresses food wastage during transportation and logistics. Reinforcement learning creates adaptive systems and prescriptive intelligence, utilising AI and machine learning, to optimise routes to reduce resource wastage. Data-driven simulation modelling aids in decision-making by providing insights into complex food systems. These technologies contribute to a more efficient and sustainable supply chain through minimising food wastage in transportation and logistics processes (Javaid et al., 2022).

Finally, the adoption of a CPS framework, which includes various sensors and network platforms, can improve automation in the food industry. This leads to greater productivity and labour efficiency, as noted by Wang et al., (2021).

11. Discussion and Synthesis: Utilisation, Benefits and Challenges of I4 Technologies for achieving CE in FSC

11.1. Utilisation and Benefits

The in-depth analysis of the I4 technologies highlights the fact that different technologies enjoy different points of access into the FSC. Technologies vary in their potential contribution to different stages of the FSC, and hence their deployment may be more prevalent in certain stages than others. The compatibility of technologies with different stages of FSC is shown in Figure 5.

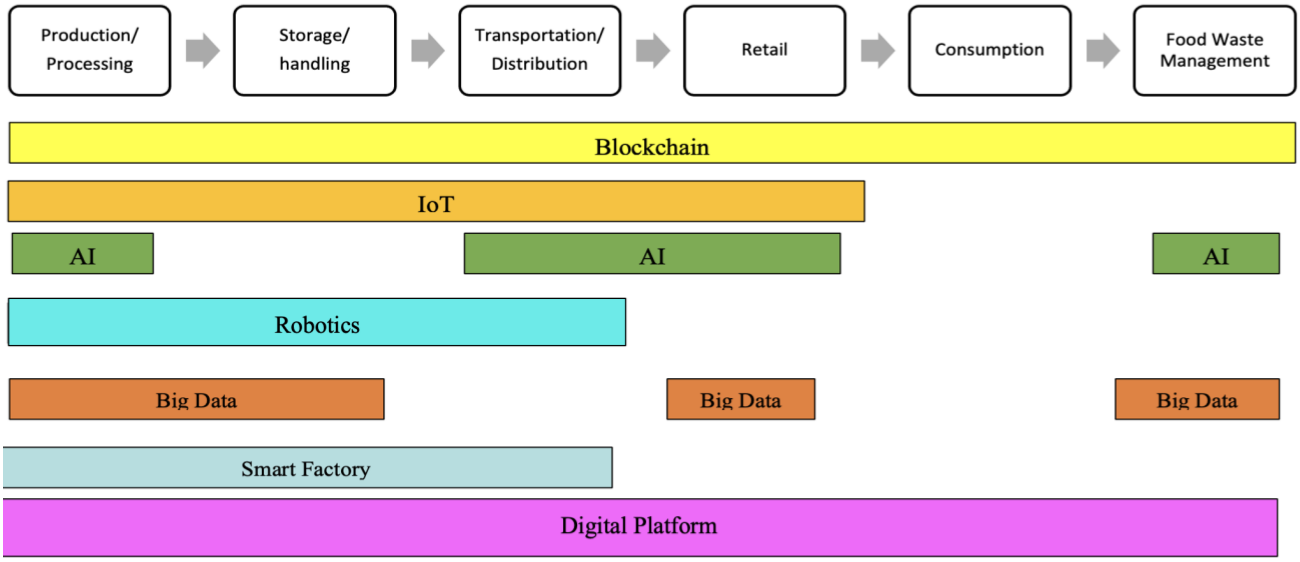

Figure 5. Use of I4 Technologies across different Stages of FSC in CE - This diagram visualises how each technology is useful within different stages of the FSC in achieving a CE. *(Source: Author's work)*

Utility and benefits for CE of I4 technologies for FSC are presented in Table 4. IoT primarily advances reduction and predictive optimisation. They can be deployed on farms, storage facilities, and retail points to monitor food conditions (temperature, humidity, spoilage indicators) in real time, triggering interventions that prevent spoilage and reduce waste. Blockchain platforms primarily enable redistribution and traceability. They create immutable ledgers for tracking food products from farm to fork, which not only increases transparency and trust but also facilitates the retrieval and recycling of products (for instance, by verifying the source and quality of surplus food destined for upcycling). AI and machine learning algorithms can analyse large datasets on production, inventory, and consumption to optimise supply chain decisions – for example, accurately forecasting demand to avoid overproduction and using predictive analytics to repurpose by-products. BDA connects these elements across the supply chain by quantifying resource flows. Digital collaboration platforms (supported by cloud computing and BDA) can connect food producers, distributors, and recyclers, matching surplus or waste from one actor with input needs of another, thereby keeping resources in use. Robotics and smart factories enhance operational efficiency and waste minimisation. Together, these technologies form a mutually reinforcing ecosystem that can transform linear food chains into circular, data-driven systems. This synthesis underscores that digitalisation and circularity are not parallel trends but interdependent processes within sustainable food transitions.

Table 4. Impact of I4 technologies in the FSC for CE - This table describes the utilities and benefits each technology provides as per our study in the FSC for achieving a CE, as well as the barriers to achieving their full potential. *(Source: Author's work)*

I4 Technology	Utility	Benefits	Barriers
Blockchain	Track and trace	Increased transparency	Society-Lack of awareness and education
	Monitoring	Increased safety, reduced food spoilage risk	Operation- Network Scalability & Interoperability
	Inventory management	Reduce transportation and storage costs	Economic benefits vs Costs
	Manage order placements	Optimise demand and supply requirements	

Table 4 (cont.). Impact of I4 technologies in the FSC for CE - This table describes the utilities and benefits each technology provides as per our study in the FSC for achieving a CE, as well as the barriers to achieving their full potential. *(Source: Author's work)*

I4 Technology	Utility	Benefits	Barriers
Artificial Intelligence	Predictive analytics	Predicting breakages and preventing food loss	Operation-Data quality and availability
	Data on product lifecycle	Increasing supply chain efficiency	Institutional-Regulatory and compliance issues
	Monitoring and tracking	Predicting supply and demand	Institutional- transparency and regulation
Big Data Analytics	Increased supply chain management and traceability	Reduced food loss and wastage	Operation-communication efficiency and system architecture requirements
	Data management in real-time	Increased production efficiency	Economic-High costs
	Evaluate shelf life	Reduced unsold food	Operation-Data quality and availability
Internet-of-Things	Temperature and humidity control	Reduced food deterioration	Economic-High installation and maintenance costs
	Data collection	Recalling faulty food products in-time	Government Policy-Threat to network security and data privacy
			Operation- Not always useful in data collection due to complex SC
Robotics	Examining supply chain stages	Identifying breakage early in the supply chain	Government Policy- Regulatory and compliance hurdles
	Environmental control	Reduced transportation costs and food loss	Government Policy-Integration issues with existing legacy systems
Smart Factory	Automated sorting	Increased production and reduced costs	Social- Skill and training taps
	Minimizing human involvement	Reduced spoilage, delays, mismanagement	Government Policy- Data security and privacy concerns

Specific I4 technological products or platforms (case studies) presented previously throughout the study represent the use of core I4 technologies in commercial products, providing additional evidence of the utilisation of the technologies in real-world solutions and their alignment with CE for FSC. These are summarised in Table 5.

Table 5. Impact of I4 real-world platforms (13 case studies) in the FSC for CE - This table summarises the 13 case studies identified for our study, the core technology and its primary function used in each study to reduce food waste and its broader alignment in achieving CE. *(Source: Author's work)*

Platform	Core Technology	Primary Function	Waste Reduction Focus	Broader CE Alignment
IBM Food Trust	Blockchain	Traceability	High	Strong
Siemens MindSphere	IoT + Digital Twins	Smart Manufacturing	Medium	Strong
Afresh	AI	Fresh Inventory Optimization	High	Strong
FoodLogiQ	Cloud + Blockchain	Traceability & Compliance	Medium	Medium
Too Good to Go	Mobile AI Platform	Surplus Redistribution	High	Strong
TE-FOOD	Blockchain + QR Code	Farm-to-Fork Traceability	Medium	Medium
Orbisk	AI + Machine Vision	Food Waste Monitoring	High	Strong
BioTrak	Blockchain + IoT	Cold Chain Monitoring	High	Strong

Table 5 (Cont.). Impact of I4 real-world platforms (13 case studies) in the FSC for CE - This table summarises the 13 case studies identified for our study, the core technology and its primary function used in each study to reduce food waste and its broader alignment in achieving CE. *(Source: Author's work)*

Platform	Core Technology	Primary Function	Waste Reduction Focus	Broader CE Alignment
Fresho	AI Ordering Platform	Wholesaler Order Optimization	High	Strong
Nestlé AI Integration	AI Systems	Predictive Logistics	Medium	Medium
GreenFense	AI + IoT	Waste Valorisation & CE Routing	Medium	Strong
Walmart Food Trust	Blockchain	Rapid Traceability & Recall	High	Strong
SmartNoshWaste	Blockchain + AI + Cloud	Smart Food Waste Reduction	High	Strong

11.2. Challenges in adopting I4 technologies for Food systems CE

The various I4 technologies face challenges in adoption and implementation. Some challenges are common to many of the ecologies, while others are more specific. Challenges such as non-standardised architectures, high installation costs, and system vulnerabilities are recurring features (Oliveira et al, 2023). However, a deeper understanding of the specific challenges and barriers of the various technologies is crucial for successfully implementing these technologies across the FSC (Javaid et al., 2022).

Implementing IoT in the FSC involves various challenges, including technical, institutional, social, economic, infrastructural, and organisational challenges. A comprehensive approach, including technological innovation, collaboration, and standardised industry practices, is crucial to addressing these challenges effectively (Ahmadzadeh et al., 2023).

It has been noted that technological advancement and innovation alone do not contribute towards sustainability. A linear economy is only focused on extracting raw materials and delivering goods to end users. In the process, it damages the environment and generates economic and social issues. Hence, CE practices are important for achieving holistic development and sustainable performance. (Dantas et al., 2021).

In another study, Ramanathan et al. (2023) studied 9 European companies and found that implementing BDA and IoT technologies in food waste management faces common challenges. A major concern is data security and privacy, with stakeholders hesitant to share sensitive information due to fears of hacker attacks and potential damage to brand image from perceived inefficiencies.

Incorporating robotics in food manufacturing, especially in developing countries, faces significant challenges. While robots can assist with labour-intensive tasks such as crop cutting and field maintenance, their use in more intricate food production processes is complex (Barasa and Etene, 2023). Managing food with robotics presents challenges due to the absence of standardisation and the varied attributes of food items. Identifying appropriate gripping surfaces and determining optimal gripping orientations becomes an intricate task. The soft texture of many food items, including fruits, meat, and bread, poses a significant challenge, making them susceptible to damage when handled by rigid mechanical grippers. Therefore, adapting handling techniques with variable force levels based on different food items' texture, consistency, and fragility is crucial to prevent damage (Barasa and Etene, 2023).

However, managing household food waste with anti-food waste apps faces its own set of challenges. The success of these apps, which often use QR codes for tracking food, depends on how they are implemented and the available infrastructure. Digital QR codes enhance accessibility and traceability, yet they may face security risks, including man-in-the-middle attacks and data integrity issues (Dey et al., 2022).

12. Policy Recommendations

The preceding synthesis highlights both the potential and the practical challenges of applying I4 technologies for circularity in food systems. Translating these insights into actionable strategies requires supportive policy measures that align technological innovation with CE goals. The following table 6 below outlines key policy recommendations derived from the preceding analysis.

Table 6. Policy Recommendations - This table provides further policy action to be taken for different stakeholders, derived and concluded from our study, analysis and empirical evidence. *(Source: Author's work)*

Recommendation	Description	Example or Justification
National Digital Food Traceability Mandates	Mandate digital traceability (blockchain, IoT, RFID) for high-risk food products to improve recall efficiency.	IBM Food Trust at Walmart reduced traceability time from 7 days to 2.2 seconds.
Smart Subsidies for Tech Adoption in Agrifood SMEs	Subsidize SME tech adoption with conditions on CE-aligned reporting.	Siemens MindSphere enabled 25% water reduction through digital twins.
Incentives for Surplus Redistribution through IoT blockchain	Provide tax incentives for verified redistribution of surplus food.	Too Good To Go incentivizes resale of surplus food through an app.
Incorporate I4.0 into Food Waste Legislation	Require public food programs to adopt AI/IOT for inventory and waste management.	Afresh reduced waste by 25–30% in institutional settings.
Enhance Interoperability of Existing Traceability Platforms	Adopt open data standards and APIs to ensure cross-platform compatibility.	TE-FOOD and FoodLogiQ need unified data standards to maximize impact.
Integrate Predictive AI in All Chain Stages	Expand AI use upstream to include crop, harvest, and spoilage prediction.	Nestlé integrates AI from manufacturing to personalized nutrition.
Build Multilingual and Low-Tech Interfaces	Design platforms with multilingual, offline, and SMS capabilities for inclusive access.	Critical for rural areas and smallholders in LMICs.
Mandate Waste Valorization Modules through AI and IOT in food preparation institutional settings	Incorporate modules to redirect unavoidable waste to composting, feed, or energy recovery.	Orbisk and GreenFense connect food waste data to local CE solutions.

13. Conclusion and contributions

This study contributes to the CE literature by synthesising recent advancements in I4.0 technologies, such as IoT, blockchain, AI, robotics, smart factory, and BDA, that support circularity across the FSC. Through a systematic review of peer-reviewed articles and analysis of real-world case studies, the research identifies both the opportunities and limitations of these digital tools in enabling circular practices. By applying a scoring mechanism to evaluate the relevance and impact of each technology, this study offers a novel framework for assessing digital readiness and circularity potential in FSC.

Findings reveal that IoT is currently the most widely adopted technology, with demonstrated benefits in real-time monitoring and supply chain optimisation. Blockchain and AI show high potential but remain underutilised due to technical, infrastructural, and social barriers.

Importantly, the review highlights critical barriers, including data privacy concerns, lack of digital infrastructure, managerial inertia, and fragmented regulatory standards, that must be addressed to enable broader adoption. As such, the paper offers the following way forward:

For practitioners, there is a need to invest in scalable digital solutions and collaborate across supply chain tiers to improve traceability, reduce overproduction, and close material loops.

For policymakers, targeted support is essential, such as incentives for SMEs to adopt digital tools, clearer regulatory frameworks for data governance, and public–private partnerships that de-risk innovation. Policymakers should establish supportive frameworks that incentivise accelerated adoption of I4 tools in circular FSC. This could include developing standards for data sharing and interoperability (to overcome fragmentation in digital platforms), providing fiscal incentives or subsidies for companies investing in IoT-based waste tracking and blockchain traceability systems, and updating regulations to recognise and reward waste-reduction innovations. By mandating transparency (for example, through blockchain-enabled reporting of food waste and resource reuse) and supporting training programs for digital skills in the agri-food sector, government policies can directly address key barriers and enable the scalability of these technologies. Such targeted policy measures will ensure that digital innovations translate into tangible CE outcomes, like reduced food waste and improved resource recovery, thereby aligning industrial practice with sustainability goals.

For researchers, by integrating a systematic literature review with practical insights from recent case studies, this study offers a comprehensive and up-to-date overview of how I4.0 technologies can catalyse circular transformation in the global food system, moving from fragmented digital adoption to a more systemic, connected, and sustainable supply chain landscape.

While this study provides a comprehensive review of I4 technologies in circular FSC, several limitations must be acknowledged. First, the analysis is based solely on published, peer-reviewed literature and publicly available case studies. This approach may overlook insights from ongoing or unpublished industry projects, pilot initiatives, or grey literature, leading to potential publication bias. Additionally, the databases selected—Web of Science, ScienceDirect, and Scopus—may not fully capture relevant contributions from regional journals or interdisciplinary sources beyond the core fields of supply chain and engineering.

Second, the rankings of technologies were derived from the frequency and prominence of their appearance in the reviewed literature, which, while indicative of academic focus, may not directly reflect their actual implementation level or practical impact in real-world supply chains. For instance, technologies with strong industry traction but limited scholarly attention may be underrepresented in the findings.

Future research should aim to address these limitations through more targeted empirical investigations. It could build on this review by applying quantitative modelling, empirical performance indicators, or longitudinal data to evaluate the impact of digital technologies on food waste reduction and circularity outcomes. Evaluating the tangible outcomes of employing IoT, AI, and blockchain, such as reductions in food waste, emissions, or cost savings, would provide critical evidence of real-world effectiveness. Furthermore, future studies could explore the financial, social, and organisational barriers to digital adoption, including investment costs, skill gaps, change resistance, and regulatory uncertainty. Comparative case studies across regions or supply chain segments could illuminate contextual factors that influence success. Integrating perspectives from both academic and industry stakeholders through surveys, interviews, and participatory methods would also enrich understanding and guide more inclusive, scalable strategies for embedding CE principles through digital innovation.

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Data Availability The research presented is mainly qualitative in nature; therefore, no quantitative datasets were generated or analysed. The "data" consists of the conceptual frameworks, expert observations, frequencies, and syntheses of Industry 4.0 technologies within the circular economy, all of which are fully documented within the manuscript and its figures.

Declarations

Competing Interests The authors declare no competing interests.

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