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Leveraging blockchain technology to augment food waste reduction in food supply chain: a systematic review

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ABSTRACT

The global stability of the Food Supply Chain (FSC) is heavily threatened by the widespread prevalence of Food Waste (FW) at every stage of the human supply chain. Rapid population growth, coupled with constrained production, continues to undermine Food Security (FS). Addressing the inefficiencies within the FSC is challenging without technological intervention. Blockchain Technology (BT) emerges as a powerful solution, contributing enhanced traceability, transparency, and accountability among FSC actors. This study examines BT's potential for reducing FW and identifies the key challenges hindering its adoption. Results reveal that BT can track food movement, identify exit points and causes of waste, and monitor the operations of the FSC. However, the realization of these benefits is significantly hindered by factors such as low digital literacy, actor diversity, inadequate digital infrastructure, high costs, poor digital data governance, and limited adaptability. By detailing both the benefits and challenges of BT implementation, this study contributes actionable insights for leveraging BT to address FW within the FSC. The study emphasizes the critical need for collaboration among all FSC stakeholders. In the current competitive global landscape, achieving sustainability increasingly depends on integration of advanced technologies like blockchain.

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1. Introduction

Food Waste (FW) occurring at the end of the supply chain has recently raised significant concerns worldwide. Findings from the United Nations Environment Programme (UNEP, 2024) reveal that 19% of food intended for human consumption is wasted globally, spanning the retail, households, and food service sectors. This level of FW threatens the stability of key dimensions of Food Security (FS), including food availability, accessibility, and utilization, while also creating significant social, environmental, and economic challenges (Omar et al., 2023). Consequently, controlling FW has become a critical issue within the FSC (Park & Li, 2021; Wünsche & Fernqvist, 2022; Yontar, 2023).

Researchers are increasingly focused on developing sustainable mechanisms to manage FW among the diverse actors in the FSC. The amount of FW varies widely across income levels: for instance, the average annual household per capita FW is highest in upper-middle-income countries (88 kg), followed by lower-middle-income countries (86 kg) and high-income countries (81 kg). However, lower-income countries lack sufficient data (UNEP, 2024). Understanding the factors that lead food to become waste at different points in the consumption chain is fundamental to designing effective strategies for its control. These strategies must address FW at retail, food service, and household levels (Kayikci, Durak Usar, et al., 2022) to develop comprehensive and sustainable solutions.

Food is often wasted unintentionally, making it difficult to identify the points where food exits the supply chain and the underlying causes of this waste (Ghaziani et al., 2022). Effectively addressing this issue requires a system that can monitor the actions of actors within the FSC and trace the consequences of these actions, particularly those that contribute to FW (Wünsche & Fernqvist, 2022). Traditional transaction methods, however, are insufficient for achieving such comprehensive traceability.

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Efforts to develop efficient solutions for mitigating FW and promoting sustainable consumption patterns have led to the application of advanced technologies. Traceability systems, for instance, enhance the efficiency and accountability of actors in the food value chain (Ciccullo et al., 2021; Gkogkos et al., 2023; Krstić et al., 2023; Ramanathan et al., 2023; UNEP, 2021). However, inadequate technological infrastructure often undermines the effectiveness of these innovations, presenting a significant challenge to their successful implementation (Mangla et al., 2021; Patidar et al., 2023).

In the era of Industry 4.0, Blockchain Technology (BT) stands out among pioneering innovations like the Internet of Things (IoT) and Big Data Analytics for its transformative potential in the FSC (Kumar et al., 2023; Sharma et al., 2023; Wünsche & Fernqvist, 2022). BT has revolutionized internal and external integration across economic sectors. While its implementation is complex, BT enhances trust, security, efficiency, and operational memory in distribution and exchange systems. Research indicates that digitizing the FSC with BT can significantly improve efficiency, enhance traceability, and promote sustainability (Dehghani et al., 2022; George & Al-Ansari, 2023; Kumar et al., 2023; Lahane et al., 2023). These capabilities make BT a promising solution for addressing the challenges faced by modern FSCs.

BT offers innovative methods for monitoring and managing the FSC through enhanced traceability. This capability allows for the identification and tracking of waste across various actors and stages of the chain, from production to consumption (Chandan et al., 2023; Colicchia et al., 2023; Kamilaris et al., 2019; Kayikci, Durak Usar, et al., 2022; Pakseresht et al., 2023). Researchers increasingly recognize BT as a pivotal approach to advancing sustainability in food systems, particularly in response to escalating food demand that outpaces population growth (Friedman & Ormiston, 2022; Mangla et al., 2021; Pakseresht et al., 2023).

Improving efficiency in the FSC through BT not only enhances sustainability but also supports the growing demand for food. By enabling better management of food waste and more efficient use of resources, BT contributes to building a more resilient and adaptive food system (García-Flores et al., 2019). These advancements underscore BT's potential to transform modern FSC operations and support global food security.

1.1. FW challenges in FSC

The FSC consists of several stages, including production, storage, processing, distribution, and consumption. Each stage contributes to FW generation, depending on factors such as the type of food, processes involved, and handling practices (Galanakis et al., 2021; Veselá et al., 2023). Various players or agents participate in activities across these stages, as outlined in Table 1. Understanding the roles of these agents and their influence on FW is crucial for developing targeted strategies to reduce waste throughout the FSC.

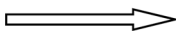

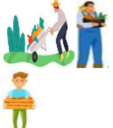



Table 1 presents the stages of the FSC activities and the inefficiencies that occur in the respective stage. Spending on avoidable cost and spoilage occurs throughout the chain. Depending on a particular food type the flow may differ and wastage in each stage also differ. Thus in every stage of the FSC different inefficiencies may occur and wastage differ between food groups and types.

1.2. Leveraging BT technology

BT originated with the development of Bitcoin, the first cryptocurrency, introduced by Satoshi Nakamoto in 2008 (Kamilaris et al., 2019). Designed as a decentralized system, BT functions as a digital transaction ledger within a peer-to-peer network. Each transaction is recorded in blocks containing transaction data, timestamps, and links to preceding blocks. Specialized software processes and presents this data in a readable format for users (Rezaei et al., 2023).

Each new block in the chain contains a hash derived from the previous block, ensuring the immutability of the data. Any unauthorized changes result in mismatches that render the entire chain invalid. To maintain integrity, BT relies on consensus and validation by all participating computer nodes in the network (Nakamoto, 2020). BT's design principles have catalyzed the development of various systems, including private blockchains, Bitcoin, and federation systems like Quorum (Kamilaris et al., 2019). These innovations demonstrate BT's versatility in supporting secure, transparent, and efficient digital transactions.

Table 1. Stages of the FSC and inefficiencies leading to FW.

Stages Flow	Production	Handling	Processing	Distribution	Consumption
					
Activities	Animal husbandry Cultivation Cooking	Transport Storage Preservation Packaging	Cooking Packaging Preservation Mixing Chopping, Slicing	Storage Packaging Transportation Assembling	Eating Food details Portioning Retail buying
Inefficiencies					
Low production	√				
Avoidable cost	√	√	√	√	√
Contamination		√		√	√
Rodents	√	√		√	
Droppings	√	√	√	√	√
Poor portioning	√	√			√
Spoilage and expire	√	√	√	√	√
Unethical behavior			√		√
Doubtful purchases			√	√	√
Over natural resources utilization	√		√		√

Source: Author's design.

Moreover, BT operates distinctly from traditional centralized systems (Konfo et al., 2023). It relies on a decentralized network of interdependent computers, known as nodes, to store information chronologically in blocks, which collectively form a chain (Rezaei et al., 2023; Wang et al., 2021). Unlike centralized systems, BT does not depend on a central authority. Instead, nodes achieve consensus through validation mechanisms, such as proof of stake or mining, ensuring agreement across the network (Kamilaris et al., 2019). Once a block is added to the chain, it is highly secure and cannot be altered. These immutable blocks form a shared digital ledger accessible to all participants, enhancing transparency across the network (Kamilaris et al., 2019; Mangla et al., 2021; Park & Li, 2021). This transparency enables monitoring of participants' actions, tracing of activities, and provision of timely information, ultimately improving efficiency throughout the chain (Bosona & Gebresenbet, 2023; Rezaei et al., 2023).

Since its initial use in cryptocurrencies, BT has been customized to enhance efficiency in various industries and sectors. It is now widely applied in tracking patients' health, managing charity operations, enabling smart contracts, distributing goods, facilitating electronic voting systems, verifying digital signatures, and maintaining administrative records (Kamilaris et al., 2019). BT's integration into governmental operations, as well as private and public business activities, has catalyzed a significant revolution in operational efficiency, earning it the reputation of a game changer (Patidar et al., 2023; Yadav & Singh, 2020). Its potential to optimize the FSC and reduce FW is particularly noteworthy and warrants serious consideration (Dehghani et al., 2022; Zhao et al., 2023).

1.3. BT and FSC

The FSC is complex, involving numerous actors working to meet growing food demand. Globalization has further intensified interactions among these actors, adding new layers of complexity. To ensure sustainable operations, the FSC requires transparency, security, and trust among all participants (Benyam et al., 2021; Patidar et al., 2023; Yadav & Singh, 2020). However, this complexity creates several challenges, including diminished consumer confidence in product quality, difficulties in verifying processes, the presence of intermediaries inflating food costs, and incidents of food fraud, all of which contribute to FW (Kamilaris et al., 2019; Keogh et al., 2022; Patidar et al., 2023; Sekuloska & Erceg, 2022). Any disruptions within the FSC, such as supply chain interruptions or failures in communication, can have cascading effects, jeopardizing FS and amplifying vulnerabilities (Christou et al., 2023).

BT has dramatically improved traceability, transparency, sustainability, and efficiency in the supply chain by enabling the tracking of food origins, sources, and quality (Patidar et al., 2023; Trevisan

& Formentini, 2024). Food product data is recorded digitally using BT, allowing seamless tracing of entries across production, processing, and consumption stages (Rezaei et al., 2023). This capacity aids in the identification and elimination of supply chain inefficiencies. While various studies have studied the application of BT in the FSC, few have particularly investigated its ability to minimize FW (Annosi et al., 2021; Cozzio et al., 2023; Omar et al., 2023). To address this gap, the present study examines BT's role in FW reduction and explores the challenges that hinder its implementation.

2. Methodology

This review employs the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework (Moher et al., 2009) to ensure a transparent, replicable, and rigorous process for selecting and synthesizing peer-reviewed literature on the application of BT in reducing FW. In emerging interdisciplinary fields such as BT in FSC, PRISMA offers a well-established, and valuable approach for identifying, screening, and including relevant studies based on predefined criteria.

Although PRISMA does not natively incorporate Natural Language Processing (NLP)-based content analysis, it facilitates structured categorization, in-depth thematic synthesis, and methodological transparency (Thankachan & Srinivasan, 2025). Within the context of BT, this approach allows for the exploration of recurring themes such as traceability, transparency, infrastructure challenges, governance issues, and cost-related barriers. The primary aim of this review was not to assess emotional tone or linguistic features which are best handled through NLP (Pirnaue et al., 2024), but rather to synthesize meaningful conceptual insights and thematic patterns to inform technology implementers, policymakers, and researchers. PRISMA was therefore considered appropriate for ensuring conceptual clarity and strengthening the policy relevance of the findings.

Looking ahead, future systematic reviews may benefit from integrating NLP-based techniques to uncover patterns across larger textual corpora, automate evidence mapping, and enhance large-scale content analysis in this rapidly evolving domain.

2.1. Techniques of search

A systematic search for relevant articles was conducted using Google Scholar (GS) and ScienceDirect (SD) databases, covering the period from January 2019 to December 2023. This study considered this time frame because the application of BT in food waste reduction has recently gained scholarly and practical momentum. Moreover, most of the reviews in this dimensions were published after 2019, revealing much relevance in policy with reference to sustainability, digital traceability and post-COVID resilience of food system. To ensure comprehensive coverage, backward and forward snowballing techniques were also applied by examining the reference lists and citations of included articles. The review focused on literature discussing the role of BT in FW reduction within the FSC. The search terms used included: ("Blockchain technology") AND ("food waste reduction") AND ("food supply chain"), applied across both GS and SD databases.

2.2. Inclusion and exclusion criteria

The following criteria were used to determine the eligibility of studies for inclusion in the review:

Inclusion Criteria: Peer-reviewed journal articles; Studies published between January 2019 and December 2023; Articles focusing on the application of BT to FW reduction or minimization; Studies addressing downstream stages of the FSC (i.e. postharvest handling, processing, transportation, storage, retail, and consumption).

Exclusion Criteria: Studies that focused on other technologies unrelated to blockchain; Articles addressing food management without reference to food waste reduction; Studies focused exclusively on upstream supply chain stages (e.g. on-farm production or pre-harvest losses); Non-peer-reviewed publications, theses, conference proceedings; Articles published before January 2019 or after December 2023.

2.3. Article selection and data extraction

All articles retrieved from GS and SD were imported into Mendeley reference manager. Duplicates were removed, and the remaining studies were assessed against the inclusion and exclusion criteria. This process was conducted independently by all three authors to minimize bias. Disagreements during the article selection phase were resolved through discussion and consensus. To further enhance reliability, two additional reviewers cross-checked the selected studies and validated the conclusions drawn from them. The whole process is clearly presented in Figure 1.

3. Results

3.1. Description of reviewed studies

The review encompassed twenty-three studies, with their characteristics detailed in Table 2. Four studies primarily focused on the application of BT to reduce food waste (FW) at the consumer level. The remaining studies examined aspects such as the sustainability of the BT (Park & Li, 2021; Rezaei et al., 2023; Wünsche & Fernqvist, 2022); supply chain (George & Al-Ansari, 2023; Kayikci, Subramanian, et al., 2022; Kumar et al., 2023), traceability systems (Bosona & Gebresenbet, 2023; Chandan et al., 2023), circular economy initiatives (Kouhizadeh et al., 2023; Yontar, 2023), local food systems (Sekuloska & Erceg, 2022), and dairy production (Mangla et al., 2021). These studies were selected due to their relevant discussions on reducing FW through BT applications. However, their collective scope collectively reveals a significant

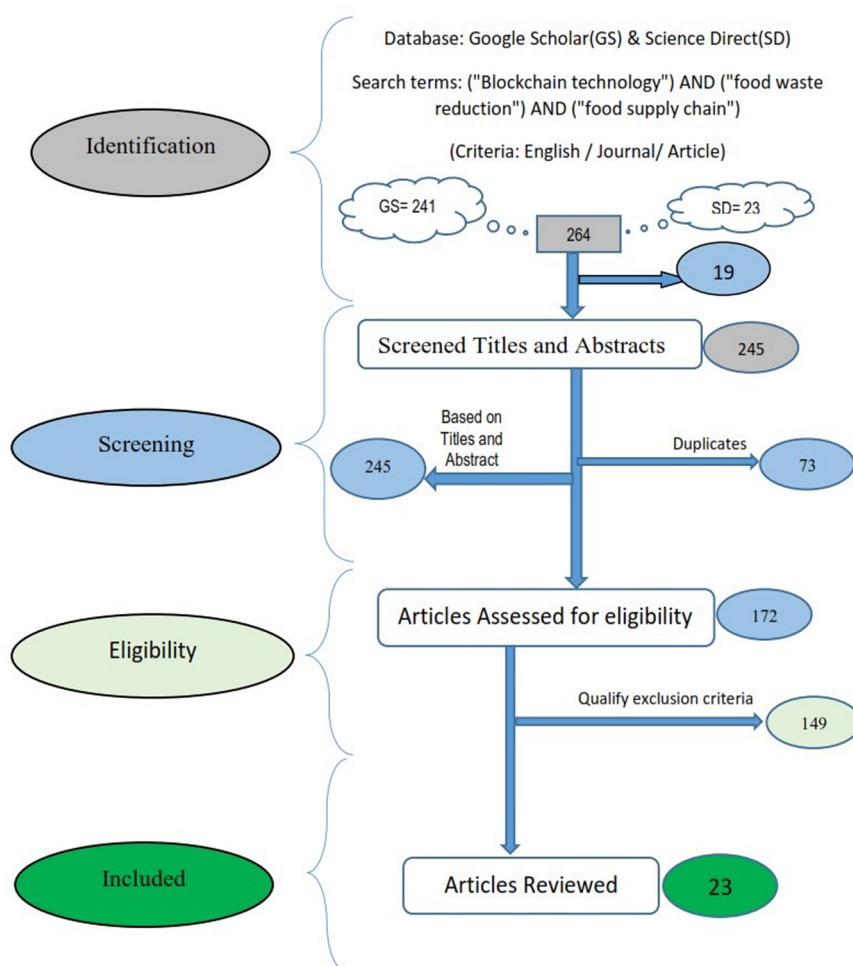


Figure 1. PRISMA diagram for selection of studies for the review.

Table 2. Summary of studies included in the review.

Author	Country	Category	Focus	Method	Journal
Marin et al. (2019)	Romania	Dairy	FW reduction using BT	Explore E-learning platform	INTED2019 Proceedings
Park and Li (2021)	N/A	BT sustainability	Sustainability of BT	Review	Sustainability
Mangla et al. (2021)	Turkey	Dairy	Impacts of BT in milk supply chains	SD modelling	Transportation Research Part E: Logistics and Transportation Review
Kayikci, Durak Usar, et al. (2022)	N/A	Perishable food supply chain(PFSC)	BT for efficiency in PFSC during outbreaks	Design System Research	International Journal of Logistics Management
Chandan et al. (2023)	N/A	SDG's	Achieving SDG's through BT along supply chain	Systematic Literature Review	Sustainability
Bhat and Dubey (2023)	N/A	Supply chain management	Overview of BT in supply chain management	Case study-Walmart	The Online Journal of Distance Education and e-Learning
Kouhizadeh et al. (2023)	N/A	Circular Economy	Performance of circular Economy and BT	Inductive reasoning & heat maps	International Journal of Logistics Management
Yontar (2023)	N/A	Circular Economy	BT success in agri-FSC management	PESTEL analysis	Environmental Management
George & Al-Ansari, 2023	N/A	BT advancement	BT application to FSC	Review	Blockchains
Wünsche and Fernqvist (2022)	N/A	Sustainable Food Systems	BT in sustainable food systems	Single case study approach	Sustainability
Rezaei et al. (2023)	N/A	Sustainable Competitive Advantage model of BT	BT in food industry	Delphi	Scientia Iranica
Bosona and Gebresenbet (2023)	N/A	Traceability systems	BT for traceability	Review	Sensors
Omar et al. (2023)	N/A	Hospitality industry	BT for FW reduction in hospitality industry	Model construction	SSRN Electronic Journal
Kumar et al. (2023)	India	Green Food Supply Chain (GFSC)	BT and IoT for green food supply transformation	Two-step ISM-ANP	Cleaner Production
Bosona and Gebresenbet (2023)	N/A	Traceability systems	BT in Agri-food production and Supply Chains	Review	Sensors
Wang et al. (2021)	China	Behavior	BT on Consumer behavior	Multimethod	Management Analytics
Sekuloska & Erceg, (2022)	N/A	Local food	BT and smart local FSC	Model Identification	Computers
Dey et al. (2022)	N/A	Application of BT	BT to Reduce FW	SmartNoshWaste	Smart Cities
Rejeb et al. (2021)	N/A	IOT and BT	Digitization of supply chain	Bibliometric review	Sustainability (Switzerland)
Krstić et al. (2023)	N/A	E-traceability	E-traceability drivers in agri-FSC	Multicriteria Decision Making Model	Agricultural and Food Economics
Tsoukas et al. (2022)	N/A	FSC	Integrating BT and TinyML	Traceability model	Information (Switzerland)
Ada et al. (2023)	N/A	Circular Economy	FSC through digital technologies	Review	International Journal of Mathematical, Engineering and Management Sciences
Kör et al. (2022)	India and Netherlands	Prevention of FW	Application of technology	Interview	British Food Journal

gap in research on this topic. Most studies were conducted in developed nations, and none focused on Africa during the analysis period. However, many of these studies reviewed how BT could help control and minimize FW. Scholars and practitioners are still exploring how these applications can advance current FW reduction strategies (Kamilaris et al., 2019).

3.2. Blockchain technology in addressing food waste

Although few studies have assessed the role of BT in addressing FW, existing research highlights BT's potential to manage the drivers of FW (see Table 2). Therefore, the application of BT for this purpose should not be underestimated. BT has significantly contributed to controlling FW by enabling

stakeholders across the FSC to trace how food is produced, packaged, cooked, and supplied, as well as the reasons for waste (Chandan et al., 2023; Rezaei et al., 2023). This preliminary control allows stakeholders to understand their role in the supply chain and identify factors leading to wastage (Chandan et al., 2023; Kayikci, Durak Usar, et al., 2022). Furthermore, BT enhances traceability and accountability among different actors in the FSC, ultimately reducing inefficiencies from production to consumption (George & Al-Ansari, 2023) while ensuring food quality and safety (Kayikci, Durak Usar, et al., 2022).

Innovations in BT have created interfaces that overcome physical limitations such as time, space, capability, and trust. Moreover, well-designed systems address the challenges of information asymmetry in traditional business models and enhance operational rationality and competition. This reveals BT's potential for managing FW and supporting environmental sustainability (Friedman & Ormiston, 2022; Park & Li, 2021; Sekuloska & Erceg, 2022; Yontar, 2023).

Low-quality food is more likely to be wasted (Yontar, 2023), and dynamic food flows raise important concerns about the quality of such products. BT enables the tracing of movement of food among various actors in the FSC (Friedman & Ormiston, 2022; Rejeb et al., 2023), which is crucial for ensuring consumer grade quality (Rezaei et al., 2023). By tracking food from production to consumption, BT helps identify points where food is damaged, enabling the development of mechanisms to address quality issues. This ensures that the final product is of consistently high quality, earning consumer confidence.

High-quality food is more durable, gains easy access to the food market, and experiences minimal waste at the consumer level (Wang et al., 2021). Digital traceability within the FSC can further identify points of spoilage and contamination (Bosona & Gebresenbet, 2023; Krstić et al., 2023). Digitizing food systems with BT not only allows contamination points to be identified and addressed, but also prevents further spoilage by enabling timely interventions (Dey et al., 2021; Tsoukas et al., 2022). This capability also supports the use of smart contracts with audit reports from trusted food market participants. However, nearly 33% of food is wasted due to spoilage caused by poor management. Without technological efficiency, traditional mitigation strategies remain limited in effectiveness (Bosona & Gebresenbet, 2023).

Supply chain transparency and food safety are bolstered through BT (Chandan et al., 2023; George & Al-Ansari, 2023; Kouhizadeh et al., 2023; Rejeb et al., 2023). Substandard or unsafe food products from the black market are intercepted by authorities and disposed of based on health or quality concerns. These products often fail to meet nutritional standards. When such items enter the market, they can cause health risks and insecurity among consumers. Even if they pass through the quality management framework, many are ultimately wasted (Chandan et al., 2023; Cozzio et al., 2023; Kumar et al., 2023). BT plays a crucial role in ensuring transparency within the food chain, holding actors accountable, and providing confidence to all stakeholders (Dehghani et al., 2022; Friedman & Ormiston, 2022). Furthermore, it enhances the resilience of the supply chain, helping it respond effectively to food emergencies (Kayikci, Durak Usar, et al., 2022).

The Food Industry Forecast (FIF) (Sekuloska & Erceg, 2022) reports that 84% of consumers prefer locally sourced food within 150 miles. Another study by Cozzio et al. (2023) highlights how BT ensures chain visibility, verifying local origins; it also shape consumer perceptions of quality and nutritional value. These critical factors underscore the importance of BT in enhancing food traceability, improving supply chain sustainability, and reducing waste (Rezaei et al., 2023). However, distribution remains a significant challenge in local food networks, often resulting in wastage and supply chain losses. BT has demonstrated its potential to address these challenges by preventing waste, ensuring food safety, and satisfying consumers' desire to trace the origin of their food (Krstić et al., 2023; Sekuloska & Erceg, 2022).

Beyond traceability functions, BT also plays a pivotal role in fostering collaboration by serving as a platform for interaction among various chain actors and stakeholders. Such collaboration fosters trust, minimizes resource mismanagement, and enhances production efficiency (Chandan et al., 2023; de Almeida Oroski et al., 2023). Additionally, integrating BT with the sharing economy has the potential to reduce surplus food (Cozzio et al., 2023). Building on these collaborative benefits, BT further enables monitoring qualitative and quantitative behaviors among chain actors. This capability allows for efficient and accurate predictions of future behaviors and outcomes within the supply chain (Wang et al., 2021).

FW can be assessed based on the resources used, the carbon footprint generated, recyclability, and eco-friendly attribute, all aimed at reducing its environmental impact (Friedman & Ormiston, 2022; Rejeb

et al., 2023; Yontar, 2023). Tracking waste enables the development of efficient and sustainable mechanisms within food systems (Park & Li, 2021; Rezaei et al., 2023). Moreover, cloud computing facilitates access to real-time information, enabling the reevaluation of decisions and attitudes related to FW (Ada et al., 2023).

BT has proved its ability to increase FS and strengthen the FSC by managing the behavior of the chain actors (Cozzio et al., 2023; Kumar et al., 2023; Mangla et al., 2021). BT also offers significant opportunities for ensuring FS by managing FW, monitoring food production and safety, and allowing traceability in cold food chains throughout the food's journey (Park & Li, 2021; Sekuloska & Erceg, 2022; Wünsche & Fernqvist, 2022; Yontar, 2023).

These rationale for attaining enough food, surplus distributions, price monitoring, and food accessibility to qualify for security in food systems (Dehghani et al., 2022).

The integration of BT with the IoT provides significant benefits for ensuring food safety, particularly for perishable items, by maintaining optimal conditions that preserve freshness (Bosona & Gebresenbet, 2023; Cozzio et al., 2023). This integration enables precise temperature control, effective tracking of seafood, improved packaging, and seamless monitoring of regulatory compliance (Chandan et al., 2023; Dehghani et al., 2022; Kayikci, Durak Usar, et al., 2022).

3.3. Challenges of leveraging BT for controlling FW

Since its discovery, BT has proven effective in enhancing efficiency in the FSC. It plays a crucial role in controlling food safety, combating food fraud, and reducing FW. However, its implementation faces significant challenges.

A major obstacle to adopting BT is the high cost, including expenses for development, deployment, and maintenance (Krstić et al., 2023). The adaptability of BT largely depends on the actors' capacity to manage the technology (Kamilaris et al., 2019) and their perception of its benefits (Joubert & Jokonya, 2021). Implementing BT involves significant monetary and non-monetary costs (Cozzio et al., 2023). However, once the initial infrastructure is established, BT can reduce operational costs across the supply chain (Chandan et al., 2023; Kör et al., 2022; Sekuloska & Erceg, 2022). Applying technology to control FW may face resistance if the costs outweigh the value of the wasted food. Therefore, mechanisms are needed to encourage or mandate chain actors to adopt technology, ensuring commitment to food security (Kumar et al., 2023).

Digital literacy, or technical know-how, is a significant concern highlighted in many studies (Patidar et al., 2023). Limited digital skills among chain actors hinder the effective use of technology-based solutions for controlling FW and achieving Sustainable Consumption Habits (SCH). Addressing this barrier is essential to fully realize the potential benefits of these technologies (Dehghani et al., 2022; Kamilaris et al., 2019). Technical uptake depends on the availability and accessibility of core and supportive infrastructure (Sekuloska & Erceg, 2022), including reliable internet access, consistent electricity supply, and skilled technical personnel (Chandan et al., 2023). Insufficient infrastructure and a lack of technical expertise can severely limit the implementation and functionality of BT, undermining its capacity to reduce FW efficiently in real-world application.

The flow of the FSC is dynamic and varies across localities. Therefore, implementing BT requires customization tailored to specific chains. This customization, however, may introduce technical challenges that discourage adoption, as it demands specialized solutions with associated costs (Rejeb et al., 2023). Furthermore, any technical errors may necessitate immediate intervention, emphasizing the need for readily available technical expertise. Even minor delays in resolving such issues can significantly disrupt FSC operations.

Regulatory frameworks present a critical challenge, as they govern the adoption and operation of BT. If these regulations do not support seamless implementation, the potential benefits of the technology may remain unrealized. Additionally, challenges in data governance raise alarms among users; inaccurate data inputs can lead to unexpected outcomes (Bosona & Gebresenbet, 2023), ultimately eroding digital trust (Sharma et al., 2023). For BT to operate successfully, all participants in the FSC must actively engage with it (Chandan et al., 2023; Wang et al., 2021). However, FSC actors are often diverse, with varying demographic and digital readiness profiles, making widespread adoption challenging, particularly in developing nations where infrastructural and technological disparities persist.

4. Discussion

This study reviewed publications on the application of BT in reducing FW along the FSC, identifying a limited number of heterogeneous studies on the topic. The review process was robust and scientific; however, did not have any statistical pooling that could be reported from the studies. Few studies have specifically focused on the application of BT in FW management (Mangla et al., 2021; Omar et al., 2023). Most existing research has concentrated on the dairy and service industries, which can be categorized under retail and food service waste. However, this focus is insufficient, as households are the largest contributors to FW (UNEP, 2021, 2024). Innovations are needed to explore how BT can be effectively applied at the household level to reduce FW. Addressing FW at this level could significantly mitigate the substantial volume of waste generated in this category. Educating individuals about the dimensions and consequences of FW is critical, as awareness can reduce waste. While awareness can reduce waste, greater impact could be achieved if households are provided with tools to monitor their contributions to total FW over time. Such mechanisms would motivate individuals to track and manage their household's waste more effectively. Additionally, implementing systems that monitor consumption patterns and reveal actual household behaviors could be a breakthrough in understanding the actions that lead to FW. This would enable more targeted strategies for reducing waste at the household level (Wang et al., 2021).

The subject of FW remains poorly understood by scholars and stakeholders within food systems, leading to significant heterogeneity in its interpretations, definitions, and measurements. While the points at which food exits the system may vary by individual, establishing a standard measure is essential for enabling consistent trend analysis and comparisons across different waste categories. According to the FAO, food becomes waste when it is removed from the human consumption chain; this includes leftover food, spoiled food, or unwanted food that is discarded, composted, or used for animal feed or other non-human purposes. Therefore, the flow depicted in Omar et al. (2023) has been refined: food that is leftover and donated to food banks or given for human consumption (Kayikci, Durak Usar, et al., 2022) should not be classified as waste.

The study presents a flowchart in Figure 2, illustrating that food is classified as either spoiled, leftover, or unnecessary by a consumer. This food is then either donated to food banks and charities or discarded as FW.

Inadequate knowledge regarding the use of technological innovations has hindered the successful implementation of these solutions. Awareness of technology is a crucial prerequisite for effective solution deployment (Dehghani et al., 2022; Friedman & Ormiston, 2022). Continuous awareness is essential for achieving positive results, as innovations are dynamic. Research on BT is ongoing in various fields to develop solutions for specific challenges. The high illiteracy rate in developing nations poses significant

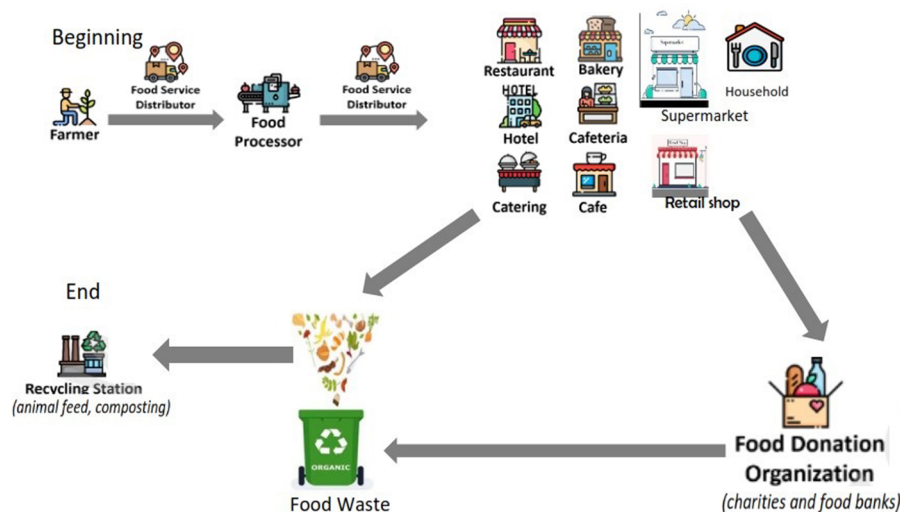


Figure 2. FSC from production to waste.
Source: Modified from Omar et al. (2023).

obstacles to the adoption of technical innovations compared to developed countries. Therefore, simplifying technology use is recommended as a viable option for both developed and developing nations, as they all face the issue of FW and share the goal outlined in SDG 12.3: to halve global per capita FW at the consumer and retail levels.

Integrating BT and IoT for FW reduction (Bosona & Gebresenbet, 2023; Chandan et al., 2023) also endorsed by (Kumar et al., 2023; Sekuloska & Erceg, 2022; Talpur et al., 2023; Wang et al., 2021) presents an effective and powerful approach in dealing with FW, ensuring real-time information in food inventory management, sufficient for quality control and efficient FW reduction strategies. Hence, it is important for developers to assess the feasibility of linking BT with other technical innovations to improve their performance in dealing with FW.

Despite the limitations of deploying BT in the FSC, governments may consider subsidizing costly stages of BT procurement and customization. Furthermore, raising awareness among supply chain actors and establishing user-friendly interfaces are critical measures. Collaborating with technology entrepreneurs can help FSC actors make affordable contributions to support sustainable BT usage. Policies such as tax breaks and exemptions for BT technologies aimed at reducing FW alongside incentives for BT infrastructure, should help to bolster these efforts.

5. Conclusion

In summary, the application of BT offers significant benefits to the food system, particularly in reducing FW, which is crucial for achieving FS. These benefits include reliability, traceability, security, and transparency (Kouhizadeh et al., 2023). The potential of BT in reducing FW is substantial (Pakseresht et al., 2023), and efforts should be made at individual, organizational, and national levels to strategize efficient food usage. These findings suggest that incorporating technology into strategies for reducing FW will enhance sustainable practices and ensure the stability of food systems. Unlike earlier studies, this research provides a detailed analysis of BT's potential in addressing the FW problem within the FSC by identifying points of food exit and monitoring operations. It also outlines the challenges associated with adopting BT. Despite the diversity among chain actors, BT demonstrates the effectiveness of technology in promoting sustainable practices.

Technology serves as a long-term, cost-effective vehicle for achieving national and international goals. Scholars should focus on developing strategies to overcome the growing challenges associated with technology use as new discoveries emerge. In today's internationally competitive market, eliminating inefficiencies across industries requires the use of BT. Future research should examine how BT functions within specific FSC contexts, particularly in underdeveloped regions where its practical utility could be transformative.

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Authors' contributions

CRedit: **Denis M. Silayo**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Writing – original draft; **Abiud January**: Conceptualization, Methodology, Resources, Supervision, Writing – review & editing; **Mary Kulwijila**: Conceptualization, Methodology, Resources, Supervision, Writing – review & editing.

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Data availability statement

The data that support the findings of this study are available from the corresponding author, [D.M.S], upon reasonable request.

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